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Integrated Operations / Payloads / Fleet Analysis Study Extension Report

Prepared by ADVANCED VEHICLE SYSTEMS DIRECTORAT
Systems Planning Division

30 September 1971

Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C.

Contract No. NASW-2129

Systems Engineering Operations
THE AEROSPACE CORPORATION

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1. INTRODUCTION

This report describes the studies accomplished from July 1, 1971 through September 30, 1971 on the extension to The Aerospace Corporation Integrated Operations/Payloads/Fleet Analysis Study (Study A). The studies were divided into four basic areas: Payload Data Bank, program risk analysis, reusable launch systems, and further analyses of the Study A final data. The status and results of the above four study areas are described in detail in the separate sections of this report, and briefly summarized below.

The Aerospace Data Retrieval System (program incorporating the Payload Data Bank) is currently being modified to incorporate payload cost data and to permit the performance of accommodation analyses. The accommodation analysis simply determines the payloads that can be captured by the Space Shuttle under varying Shuttle ground rules (e. g., cargo bay size and Shuttle payload weight capability).

The program risk analysis interrelates payload reliabilities, redundancy levels, failure warning, reliability and Space Shuttle delay times (between payload malfunction and its replacement) and system costs. High system availability can be obtained by improving payload reliability and Mean Mission Duration (MMD) at a higher cost per payload. Higher availability can also be obtained by reducing the Space Shuttle delay time, and by use of satellite failure warning techniques which can be traded off on a cost basis against increased payload reliability to achieve a desired availability.

The additional analyses conducted on the Study A final data included comparison of midterm and final cost data, cross-checks of final cost analyses and results, payload selection and cost relationships, costs associated with launch vehicle reliability and infant mortality, and various other checks to verify the resultant data output. Several changes were made to Final Report data during the three month extension period, thus invalidating much of the aforementioned analyses.

2. PAYLOAD DATA BANK

The Data Retrieval System (DARES) is currently being modified and expanded for the purpose of including payload cost data and performing the accommodation analysis. The accommodation analysis determines those Space Shuttle payloads that can be accommodated by specific alternate Shuttle payload bay sizes and performance (payload weight capability). The following two subparagraphs describe these Payload Data Bank modifications.

2.1 COST DATA INPUT IN PAYLOAD DATA BANK

The inputting of the cost data into the Data Bank will be achieved by developing a subroutine to insert the payload cost data. This subroutine, titled "Data to DARES" (DTD) will select the appropriate data from the Payload Cost Model (PALCM) and transfer this information to cards. The PALCM data is on tape. The punched cards will then be inserted into the Data Bank card deck for retrieval and printout.

In addition to the development of the subroutine, the payload characteristics for the Data Bank have been modified to list the cost data and the payload descriptors for the Payload Cost Model. The payload descriptors serve to indicate the payload complexity. These descriptors are spacecraft design factor, mission equipment design factor, type of mission equipment, and R&D fiscal funding spread.

The cost data will be listed for the basic RDT&E and unit investment costs by subsystem, and will include total RDT&E, total investment, total operations, and total payload costs. It was necessary to list cost data in this order since the basic RDT&E and unit costs will not equal the total RDT&E and investment costs. The unit costs do not include the number of units and refurbishment schedule which are factors for determining the investment cost. The schedule is determined by the capture analysis and is dependent on the launch vehicle fleet considered. Thus, to reduce the number of cost schedules, the cost data on current reusable, low cost expendable and low cost reusable payloads was based on Space Shuttle usage only (case C). This approach will limit the amount of data inputed into the Data Bank. It should be recognized that all of the payload (i.e., payload variations) costs are not available, since only the payloads selected in the capture analysis were costed.

The current expendable payloads should be based on current expendable launch vehicles to provide a baseline Data Bank. The revised payload characteristics for the Data Bank are listed in Table 2-1 and an example printout shown in Table 2-2.

2.2 ACCOMMODATION ANALYSIS

The computer program planning has been initiated and some computations have been completed for the accommodation analysis. The DARES program will be used to perform this analysis.

The output of the accommodation analysis will be a list of payloads accommodated and a list of unaccommodated payloads with reasons for rejection. Initially, only a single payload per launch will be considered, i.e., multiple payload launches will not be considered.

To perform this analysis the following inputs and computations must be performed before the accommodation subroutine can select payloads that can and cannot be accommodated:

1. Input the payload dimensions
2. Input the payload orbits and characteristic velocities
3. Input the generalized Space Shuttle performance
4. Input the generalized Space Tug performance
5. Select the Space Shuttle performance for each payload
6. Compute Space Tug performance for payloads that require high energy stages

The payload dimensions and payload orbital characteristics are in the Data Bank and can be retrieved. Elliptical orbits will be inputted into the Data

Bank in terms of equivalent circular orbits having the same energy as the elliptical orbits. The characteristic velocities have all been recomputed to five significant figures. The characteristic velocities for low earth orbits are determined for a 100 x 100 n mi parking orbit and a Hohmann transfer to mission orbit. Inclination effects are not included in the characteristic velocity for low earth orbit. For the synchronous orbits, a 100 x 100 n mi x 28.5 inclination parking orbit and a Hohmann transfer to mission orbit, including the effects of plane changes, are assumed.

For the planetary missions, the same parking orbit is assumed and the transfer orbit assumed was a minimum impulse intercept trajectory, considering the launch year. The velocities computed were generally less than the characteristic velocity listed in the Data Book, except for the Uranus Orbiter, Asteroid Survey, and Comet Rendezvous. The Uranus Orbiter velocity was probably low because the listed velocity is for the Jupiter swingby; however, for the listed launch year, Jupiter will not be in a position for assistance. The Asteroid Survey and Comet Rendezvous were also based on the Hohmann transfer method. The velocities for these three missions will be revised upwards to the computed minimum velocities.

The other listed planetary velocities are higher than the minimum computed velocities and are rationalized as the recommended velocities to provide for more favorable communication distances and/or transfer times.

The performance for the two stage, fully reusable Space Shuttle, including abort capability, is shown on Figures 2-1, 2-2, and 2-3 for the cases of airbreather engines out, airbreather engines in, and the 65,000 lb structural limit, respectively. For alternate Space Shuttle configurations, this type of performance data must be provided or computed. The Space Tug performance considered is shown on Figure 2-4. The Space Tug is defined in Volume IV of the Integrated Operations/Payloads/Fleet Analysis Final Report. For alternate Tugs, this type of performance data must also be supplied or computed.

Table 2-1. Payload Characteristics for Data Bank

Area	Characteristic	Characteristic Abbreviated	Example (fictitious)
Programmatics	Title	Title	30 Letter Entry
	Data Book Designation	Dta Bk Des	NAS-1
	Program	Program	NASA Astro
	Mission Model Designator	Payload	Baseline
	Agency	Agency	NASA or DoD
	Mission Objectives	Miss Objec	70 Letter Lines
Number Satellites in System	Number Satellites in System	No Sats	1
Characteristic Velocity	Characteristic Velocity, fps	Char Velo	26,480
	Delta Velocity, fps	Delta Velo	14,104
Orbit Parameters	Equivalent Circular Orbit Altitude, n mi	Eq Cir Or	400
	Nominal Inclination, deg	Nom Inclin	30
	Nominal Apogee, n mi	Nom Apog	400
	Nominal Perigee, n mi	Nom Perig	400
	Nominal Eccentricity	Nom Eccent	0
	Maximum Apogee, n mi	Max Apog	500
	Minimum Apogee, n mi	Min Apog	350
	Maximum Perigee, n mi	Max Perig	500
	Minimum Perigee, n mi	Min Perig	350
	Maximum Inclination, deg	Max Inclin	30
	Minimum Inclination, deg	Min Inclin	28.5
Launch Vehicles, Sites	Launch Window, days	Lch Window	20
	Launch Vehicle 1	Lch Veh 1	Titan III
	Launch Site 1	Lch Site 1	KSC 44

Table 2-1. Payload Characteristics for Data Bank (Cont'd)

Area	Characteristic	Characteristic Abbreviated	Example (fictitious)
Launch Dates	Initial Launch Date	In Lch Dat	1979
	Flights, 1979	Flts 1979	1
	Flights, 1980	Flts 1980	0
	Flights, 1981	Flts 1981	1
	Flights, 1982	Flts 1982	0
	Flights, 1983	Flts 1983	1
	Flights, 1984	Flts 1984	0
	Flights, 1985	Flts 1985	1
	Flights, 1986	Flts 1986	0
	Flights, 1987	Flts 1987	1
	Flights, 1988	Flts 1988	0
	Flights, 1989	Flts 1989	1
	Flights, 1990	Flts 1990	0
	Total Number of Flights	Total Flts	6
Lifetime	Maximum System Expected Lifetime, yr	Sys Lf	10
	Spacecraft Mean Mission Duration, yr	SC MMD	5
	Mission Equipment Mean Mission Duration, yr	ME MMD	2
	Payload Mean Mission Duration, yr	Pay MMD	4
Maintenance, Refurbishment	Type of Maintenance or Refurbishment	Typ Mnt R	Orbital
	Expected Maintenance Philosophy	Exp Mnt Ph	Optical technician(s)..
	Maximum Payload Per Visit, lb	Max Pld Vs	5000
	Minimum Payload Per Visit, lb	Min Pld Vs	5000
Launch Dimensions	Launch Volume, ft^3	Lch Volume	1570
	Launch Length, ft	Lch Length	45
	Launch Diameter, ft	Lch Diam	13
Sensors	Sensor 1	Sensor 1	TV Camr
	Sensor 2	Sensor 2	Photo Camr

Table 2-1. Payload Characteristics for Data Bank (Cont'd)

Area	Characteristic	Characteristic Abbreviated	Example (fictitious)
	Sensor 3 Sensor 4 Sensor 5	Sensor 3 Sensor 4 Sensor 5	Spctrgrphs NA NA
Pointing Accuracy	Pointing Accuracy, sec	Point Acc	NA
Power	Average Electrical Power, watts	Av E Pwr	2000
Structures Mechanisms, Vehicle Assembly Weight	Structures, Mechanisms, Vehicle Assembly Weight, lb	St W	2000
Environmental Control Weight	Environmental Control Weight, lb	Env Cont W	500
Guidance, Navigation, Stabilization Weight	Guidance, Navigation, Stabilization Weight, lb	Stab W	700
Propulsion Weight	Propulsion Weight, lb Propellant Weight, lb	Prop W Prop P W	400 350
Attitude Control (Mass Expulsion) Weight	Attitude Control (Mass Expulsion) Weight, lb Propellant Weight, lb	A C W A C P W	50 40

Table 2-1. Payload Characteristics for Data Bank (Cont'd)

Area	Characteristic	Characteristic Abbreviated	Example (fictitious)
Telemetry, Tracking, Command Weight	Telemetry, Tracking, Command Weight, lb	TTC W	300
Electrical,	Electrical, Weight, lb	Elec W	60
Mission Equipment Weight	Mission Equipment Weight, lb	Mis E W	8000
Weight Totals	Total Weight - Dry, lb Total Weight - Including Expendables, lb Adapter Weight, lb Launch Weight, lb	Total D W Total W W Adapter W Launch W	11620 12010 120 12130
Structure	Type of Structure	Type St	Exo
Propulsion	Type of Propulsion	Type Prop	Liquid
Propellant	Type of Propellant	Type Prope	Hydrazine
Attitude Control	Type of Attitude Control	Type A C	3-Axis
Electrical Power	Type of Electrical Power	Type E Pwr	Solar

Table 2-1. Payload Characteristics for Data Bank (Cont'd)

Area	Characteristic	Characteristic Abbreviated	Example (fictitious)
Mission Equipment	Type of Mission Equipment	Type ME	Comm., Hi Complex, or Low Complex
Kick Stage	Type of Kick Stage	Type Kick	Centaur
Design Factor	Spacecraft Design Factor	SC DF	0.25
	Mission Equip Design Factor	ME DF	0.25
Funding Spread	R&D Fiscal Funding Spread, yr	RD Fund Yr	4
RDT&E Cost	Structure RDT&E Cost, $M	St RD C	3
	Electrical RDT&E Cost, $M	Elect RD C	2
	Telemetry, Tracking, and Comm RDT&E Cost, $M	TTC RD C	5
	Stabilization and Control RDT&E Cost, $M	Stab RD C	10
	Propulsion RDT&E Cost, $M	Prop RD C	5
	Total Spacecraft RDT&E Cost, $M	SC RD C	25
	Mission Equipment RDT&E Cost, $M	Mis E RD C	30
	Basic RDT&E Cost, $M	Bas RD C	55
	Basic Launch Operations Cost, $ M	Bas AGE C	15
Investment Cost	Structure Unit Cost, $ M	St U C	2
	Electrical Unit Cost, $ M	Elect U C	3
	Telemetry, Tracking, and Comm Unit Cost, $ M	TTC U C	4
	Stabilization and Control Unit Cost, $ M	Stab U C	5
	Propulsion Unit Cost, $ M	Prop U C	1
	Total Spacecraft Unit Cost, $ M	SC U C	15
	Mission Equipment Unit Cost, $ M	Mis E U C	6
	Unit Invest Cost, $ M	U Inv C	21

Table 2-1. Payload Characteristics for Data Bank (Concluded)

Area	Characteristic	Characteristic Abbreviated	Example (fictitious)
Operations Cost	Unit Ops Cost, $ M	U Ops C	4
Total Payload Cost	Total RDT&E Cost, $ M	Tot RD C	70
	Total Invest Cost, $ M	Tot Inv C	22
	Total Ops Cost, $ M	Tot Ops C	6
	Total Payload Cost, $ M	Tot Pay C	98

Table 2-2. Example Printout, Revised Payload Data Bank

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10/21/71

MISS. OBJ. INDEPENDENT INVESTIGATIONS OF SOLAR AND STELLAR BEHAVIOR IN THE UV,
X-RAY AND RADIO SPECTRAL REGIONS. NOT PART OF OBSERVATORY.

PAYLOAD	PROGRAM	AGENCY	NO SATS	CHAR VELO	DELTA VELO	EQ CIP OR	NOM INCLIN	NOM APOG
CURR.EXP.	N ASTRNOMY	NASA	1	2.6174E+04	593.0	270.0	28.50	270.0
NOM PERIG	NOM ECCENT	MAX APOG	MIN APOG	MAX PERIG	MIN PERIG	MAX INCLIN	MIN INCLIN	LCH WINDOW
270.0	0.	270.0	270.0	270.0	270.0	28.50	28.50	...NONE...
LCH VEH 1	LCH SITE 1	IN LCH DAT	FLTS 1979	FLTS 1980	FLTS 1981	FLTS 1982	FLTS 1983	FLTS 1984
T3C	ETR	1979	2	0	1	2	2	1
FLTS 1985	FLTS 1986	FLTS 1987	FLTS 1988	FLTS 1989	FLTS 1990	TOTAL FLTS	SYS LF	SC MMD
0	2	1	2	2	0	15	3	*NO ENTRY*
ME MMD	PAY MMD	TYPE MNT R	EXP MNT PH	MAX PLD VS	MIN PLD VS	LCH VOLUME	LCH LENGTH	LCH DIAM
NO ENTRY	3.000	...NONE...	...NONE...	0.	0.	64	4.000	4.500
SENSOR 1	SENSOR 2	SENSOR 3	SENSOR 4	SENSOR 5	POINT ACC	AVE E PWR	ST W	ENV CONT W
TV CAMERA	UHF DETECT	C-RAY DET	VN ALN DET	LASER	10 SEC	100.0	200	15
STAB W	PROP W	PROP P W	A C W	A C P W	TTC W	ELEC W	MIS E W	TOTAL B W
40	110	80	34	20	50	161	250	760
TOTAL W W	ADAPTER W	LAUNCH W	TYPE ST	TYPE PROP	TYPE PROPE	TYPE A C	TYPE E PWR	TYPE ME
860	30	890	EXO	LIQUID	GN2	3-AXIS	SOLAR	MED.COMPLX
TYPE KICK	SC DF	ME DF	RD FUND YR	ST RD C	ELECT RD C	TTC RD C	STAB RD C	PROP RD C
...NONE...	2.000	4.000	3.000	12.81	4.531	6.490	13.10	3.424
SC RD C	MIS E RD C	BAS RD C	BAS AGE C	ST U C	ELECT U C	TTC U C	STAB U C	PROP U C
40.36	17.52	57.87	2.846	2.634	.7280	1.246	1.278	.1660
SC U C	MIS E U C	U INV C	U OPS C	TOT RD C	TOT INV C	TOT OPS C	TOT PAY C	
6.053	5.057	11.11	2.774	157.0	171.0	42.00	380.0	

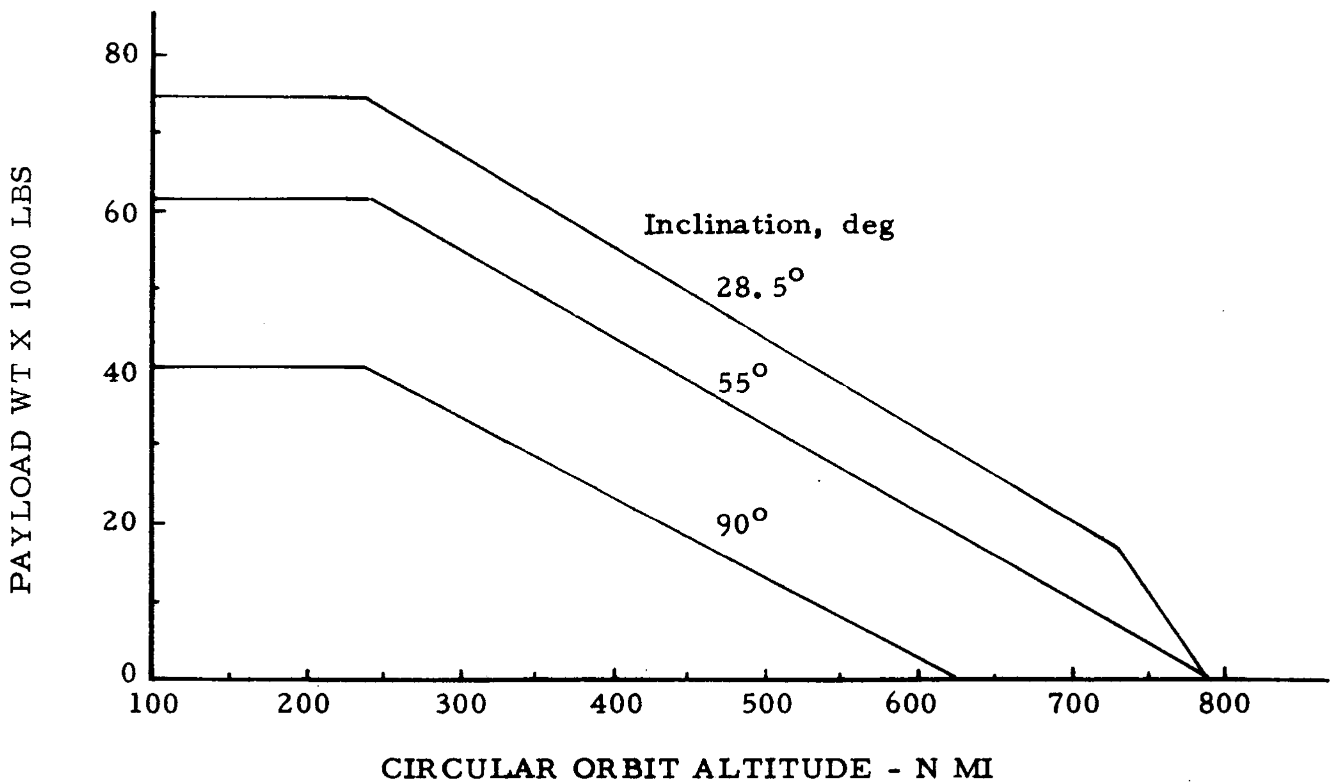

Figure 2-1. Space Shuttle Performance Capability
Payload Versus Circular Orbit Altitude, Two-Stage Fully Reusable (ABES Out)

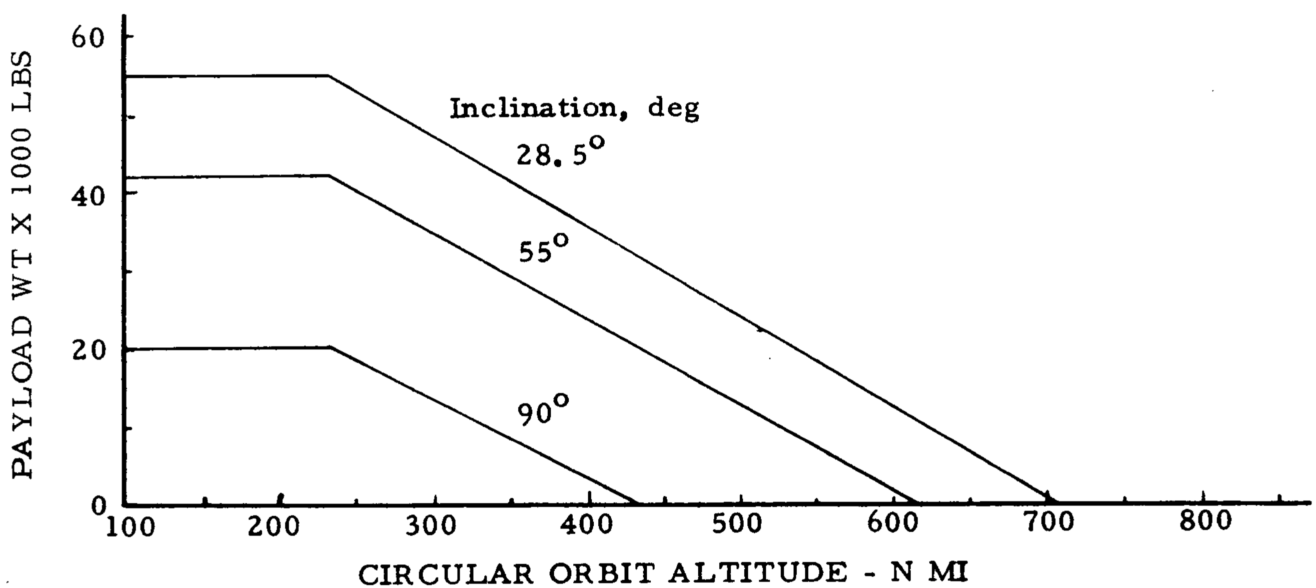

Figure 2-2. Space Shuttle Performance Capability
Payload Versus Circular Orbit Altitude, Two-Stage Fully Reusable (ABES In)

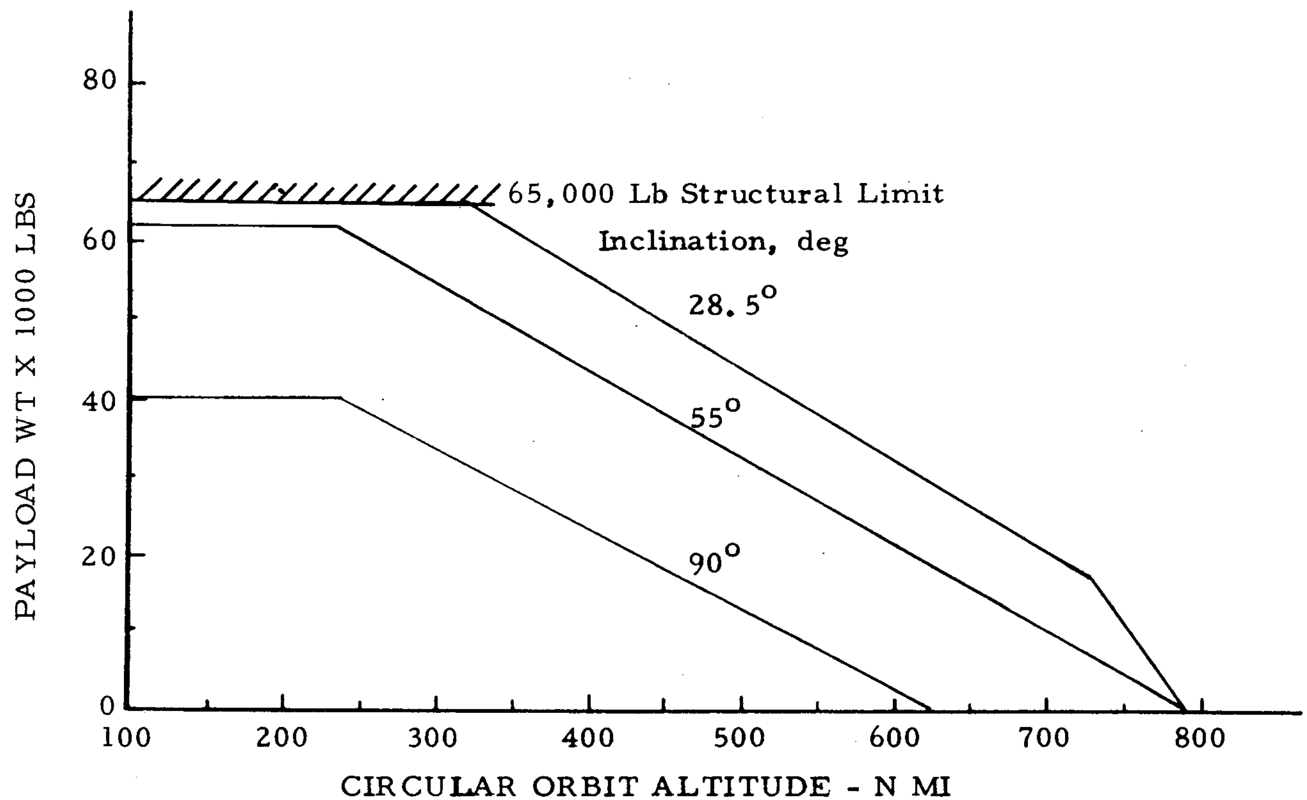

Figure 2-3. Space Shuttle Performance Capability
Payload Versus Circular Orbit Altitude, Two-Stage Fully Reusable
NASA Structural Limit and ABES Out

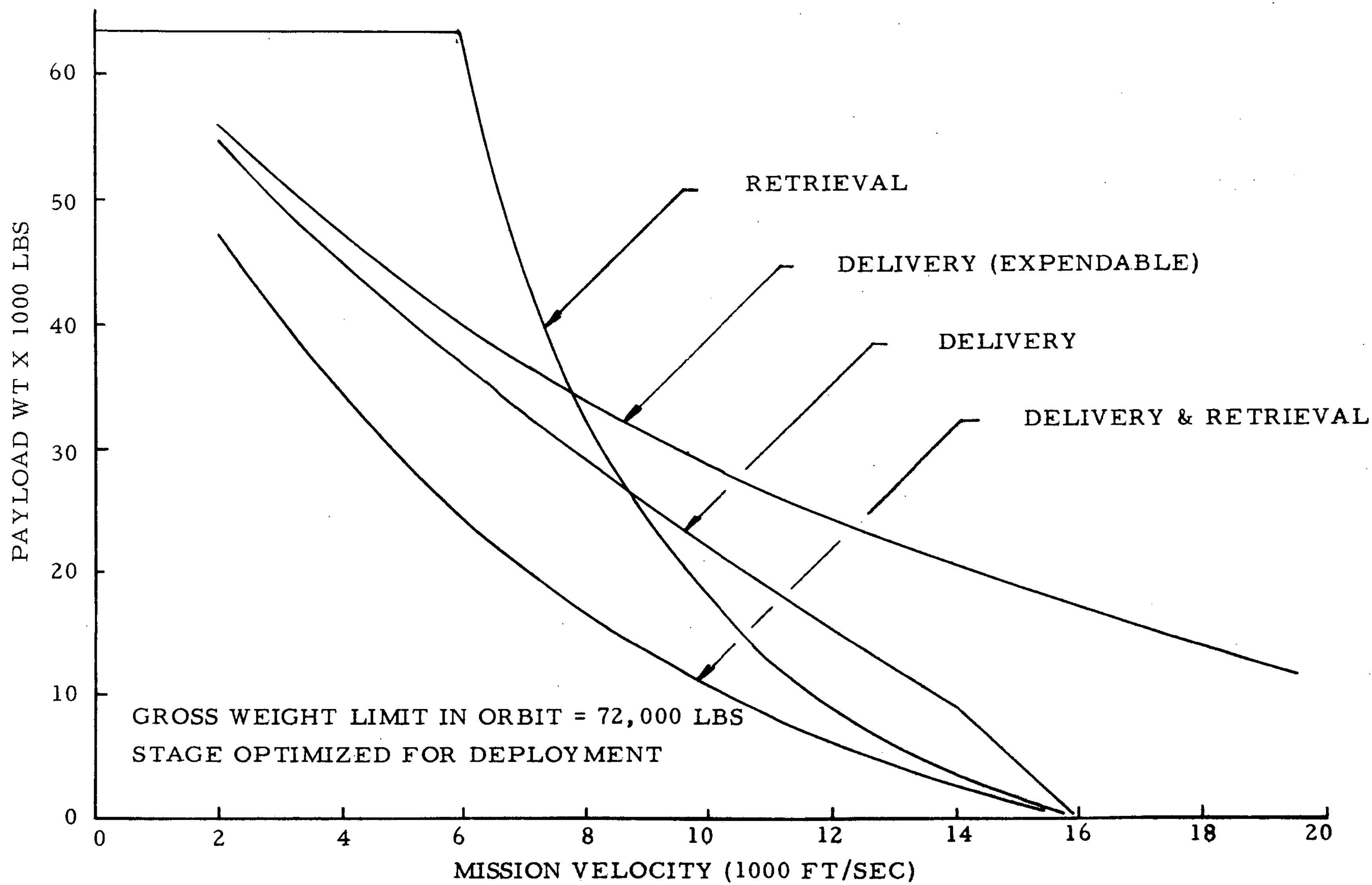

Figure 2-4. Tug Performance Capability - Single Stage

3. PROGRAM RISK ANALYSIS

In considering future applications of satellite programs for space, an area which has direct bearing on the attractiveness and competitiveness of satellite systems with ground systems is a low risk level or assured high system availability and dependability associated with an operational space system, all at a competitive cost. For instance, a communications satellite system can be run at a lower rate of return on capital investment if the system risk is low.

Space system risk levels can be reduced by utilizing the capabilities of the Space Shuttle system. It is envisioned that space system risks can be lowered so that they are comparable with present day modes of transportation and ground-based communications. The levels of confidence for investors in Shuttle-supported space systems should be comparable to those for competing ground-based systems such as airlines, highways, land lines, microwave relays, and undersea cables. It is expected that these low system risks can be demonstrated through analyses showing potentially high satellite success ratios, satellite availability on orbit, and insensitivity to system predictions (margin for error).

The problem then becomes one of showing that the low risk operational space system can be obtained using the Space Shuttle (and Space Tug) with appropriate payload design and operational approaches.

3.1 SHUTTLE CAPABILITY

The Space Shuttle capabilities which make this low risk concept possible are payload retrieval, high success ratio for launch, and flexibility of launch schedule. Low Space Shuttle operating costs compared to expendable systems help keep the costs of a low risk satellite system reasonable. Integrated Fleet Analyses[1] to date have shown that payload return can generally be combined with deployment, making the return of payloads to earth very inexpensive from a transportation point of view.

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[1] See Aerospace Corporation Report ATR-72(7231)-1, "Integrated Operations/Payloads/Fleet Analysis Final Report," dated August 1971

3.2 PAYLOAD CAPABILITIES

Analyses to date have shown that refurbishment of payload systems and continuing of repair action such as the periodic maintenance proposed for NASA Space Observatories on spacecraft and mission equipment should be primary operational modes for payloads in the Space Shuttle era. Studies have also shown the need for anomaly correction, the repair of worn-out hardware and hardware operating in a degrated mode. Payload repair and refurbishment will make low risk, high availability satellite operations possible for a reasonable cost.

Other studies indicate increased spacecraft lifetime expectancy, particularly for spin-stabilized satellites. Three-axis stabilized satellites' expected lifetimes are also gradually increasing. These longer lifetime satellites use high reliability parts and will be highly redundant; however, the system risk associated with the satellites obtaining their full expected mean mission duration is still relatively high. The system risk can, however, become quite low for a repairable mode of operation.

The lifetime for many satellites is largely determined by the lifetime predicted for experiments or mission equipment hardware. This is particularly true when, as is often the case, new technology is applied to the mission equipment. For a system featuring reusable, repairable satellites, maximum use can be made of spare spacecraft held on the ground. This is particularly true of spacecraft with a high level of redundancy and the Space Shuttle system with its inherent capability for changing flight plans and schedules to accommodate unscheduled satellite repair as well as scheduled maintenance. Shuttle launch delay from time of request for launch for satellite repair to completion of on-orbit service is one key element in risk analysis.

Other key satellite system elements for obtaining low system operating risk at a reasonable cost are:

(1) Satellite failure warning capability

(2) Adequate on-orbit checkout and operation of the satellite before the deploying Shuttle-orbiter or Tug depart the vicinity of the deployed payload.

(3) Dependability build-up through flight experience with the hardware in-hand.

3.3 OBJECTIVE

The objective of this study is to establish low risk space system goals and estimate the cost of low risk operation for space systems utilizing the Space Shuttle.

3.4 DEFINITIONS

The following terms appear frequently in this discussion:

Availability - A measure of the degree to which an item is in the operable and committable state at the start of the mission, when the mission is called for at an unknown (random) point in time. Availability over a given period of time is the ratio of the operable time during the period to the length of the period.

Mean Mission Duration - Integral of satellite survival curve from zero time to truncation time. Abbreviated as MMD.

Program Cost - Total cost to design, develop, establish, and maintain a satellite system. Includes RDT&E and investment costs, including spares. Also includes Shuttle transportation costs.

Refurbishment - Complete overhaul, repair and checkout at a ground facility. Results in a like-new satellite in terms of operating characteristics.

Risk - A general definition of risk is the probability of rendering the wrong decision based on pessimistic data or analyses. For the analysis in this report, the risk is measured by satellite availability predicted and the margin for error associated with obtaining this availability.

Shuttle Delay - The time period between a signal indicating that the satellite is failing and the time that the replacement or repaired satellite is operating. It is assumed in the analysis of this section that the decision to launch is made in advance in the case of scheduled refurbishment. Therefore, no satellite outage occurs for scheduled refurbishment. Outage only occurs in the case of random failures. Outage time is exactly equal to Shuttle delay for each random failure.

Reliability - The probability that an item will perform its intended function for a specified interval under stated conditions.

3.5 MINIMUM PROGRAM COST CONCEPT

The total cost of a satellite program can vary over a wide range, depending upon decisions made regarding execution of the program. In the analysis discussed in this section, the satellite program cost is influenced by the extent of satellite subsystem redundancy selected and the frequency of refurbishments. Scheduled refurbishments are a feature of one maintenance strategy chosen for analysis in this study. Other strategies can be examined (such as the use of warnings, see Section 3. 7. 2) which will influence total program cost. Generally, for a given maintenance strategy, changes which decrease program cost also result in decreasing system availability.

A prime objective of a program risk analysis is to define the combination of satellite redundancy and maintenance strategy which produces the minimum program cost while providing an acceptable level of system availability. This is the minimum program cost concept. Program cost versus system availability for the strategies of scheduled refurbishments and use of the warning system is discussed in Section 3. 8. 2.

3.6 SATELLITES CONSIDERED

The Program Risk Analysis includes analysis of three satellites. The first is a navigation satellite. Its design is based upon an expendable satellite design adapted to reuse, and it is called "Navsat" throughout this section. This approach was chosen because sufficient, detailed Navsat weight and reliability data were available to perform the planned analysis.

The second satellite in the analysis is the Intelsat IV. This satellite is chosen as a representative communications satellite.

The third satellite to be analyzed is the Nimbus-B. This is chosen as a representative meteorological satellite.

3.7 DESCRIPTION OF NAVSAT ANALYSIS

Two basic strategies for Navsat system maintenance have been examined. The strategies are described in Sections 3.7.1 and 3.7.2. Some of the fundamental aspects of the analysis are discussed in Sections 3.7.3 through 3.7.9. Results are given in Section 3.8.

3.7.1 Refurbishment Maintenance Strategy

In the Navsat refurbishment analysis described in this section, the Navsat system is maintained by means of the following maintenance strategy:

(1) At specified intervals of time (e.g., 3 years, 4 years), each satellite in the system is replaced with a refurbished satellite or a new satellite which is identical in operational characteristics and reliability to a new one. The satellites removed from orbit are refurbished to like-new condition at a ground facility and stored until needed.

(2) In the event of a satellite in-orbit failure, the satellite is replaced as quickly as possible by the STS. The delay time between satellite failure and first operation of the replacement satellite is a variable in the analysis. The failed satellite is refurbished at the aforementioned ground refurbishment facility to like-new condition and stored for future use.

This strategy has been examined extensively in the Navsat analysis. Results are included in Section 3.8.

3.7.2 The Warning System

The level of unavailability of a satellite is determined by the number of failures of that satellite and the period of time between satellite failure and fix. A method suggested for minimizing the occurrence of random failures has been named the "warning" system. In this system, instrumentation and telemetry are provided in the satellites to detect and telemeter failure of the next-to-last redundant element in a redundant set, thus providing a warning of potential failure to the user. Such a failure leaves only a single path out of the original redundant paths to provide successful operation. When this warning is received on the ground, a replacement satellite may be scheduled and dispatched as soon as possible to replace the operating satellite. Replacement will be expected to occur before failure of the last redundant element, thereby avoiding most of the satellite outage.

Warnings of this kind appear to have considerable promise when used judiciously. For example, a method might be devised whereby, on the basis of warnings already received, the probability of the satellite's operating satisfactorily until the next scheduled refurbishment can be assessed. On the basis of this assessment, the decision can be made when (and if) only failed components should be replaced or an unscheduled refurbishment should be accomplished. On the basis of the failure information, some or all scheduled refurbishments may be eliminated.

Strategies of such complexity are, however, beyond the scope projected for warning studies at this point. A simpler warning strategy has been examined first.

Briefly described, the maintenance strategy with warning is:

(1) A selected group of Navsat subsystem elements has been provided with a warning capability. When a warning is received on the ground, a replacement satellite is scheduled for launch and dispatched to take the place of the satellite sending the warning.

(2) In addition to replacement of satellites upon receipt of a warning, regular scheduled refurbishments are also assumed in the warning system analysis. This is similar to the scheduled refurbishment maintenance strategy discussed in Section 3.7.1.

Thus, the strategy examined is a combination of periodic refurbishment plus refurbishment upon warning (or failure).

The group of subsystem elements assumed to have been provided with a warning capability is called a "warning set." The warning set is chosen in this analysis as follows. All subsystem elements which are redundant in the least reliable (three-year MMD) satellite are placed in the warning set. When any other satellite design is assumed to be provided with a warning capability, the same group of elements is placed in the warning set. This method of selection is not necessarily optimal; the optimum is not known at this time.

As a concrete example, the warning system analysis discussed in this section has been accomplished using, as a starting point, the five-year MMD Navsat design. All subsystem elements which are redundant in the three-year MMD satellite are placed in the warning set of the five-year MMD satellite.

A change in the satellite's redundancy level becomes necessary when the warning system is used. The specific change is that all elements in the warning set are made at least triply redundant. The reason for this is as follows. If doubly redundant subsystem elements are included in the warning set, then a warning is sounded when either of the two elements fails.

Analyses of typical warning strategies have been completed. One result of the analyses is that too many satellite replacement flights result when a warning set includes doubly redundant elements, thus forcing the satellite designer to triply redundant black boxes wherever redundancy is employed.

Although the starting point in the warning analysis is a Navsat with five-year MMD, the addition of redundancy to meet the warning system requirements results in a considerably greater MMD. The reliability of the warning set satellite is shown in Figure 3-3.

3.7.3 Assumed Navsat System

Listed below are basic assumptions used in the analysis:

3.7.3.1 The Navsat system considered in this analysis consists of four satellites operating in synchronous orbit. Two criteria for availability are considered. The first criterion assumes that the four satellites operate independently like a set of communications satellites. The availability of each individual satellite is of interest rather than the availability of the whole set. The second criterion for availability assumes that all four satellites must be operating for the system to be considered available. These criteria are examined separately.

3.7.3.2 A Shuttle and Tug are required for a Navsat satellite deployment or replacement flight. The transportation cost is $4.9 per mission, and the payload launch support cost for each launch is $1.1 million.

3.7.3.3 Unit costs of the Navsats are as follows: 3 year MMD, $13 million; 4 year MMD, $13.6 million; 5 year MMD, $14.2 million; warning set Navsat, $17.6 million. RDT&E costs are as follows: 3 year MMD, $96 million; 4 year MMD, $98 million; 5 year MMD, $98 million; warning set Navsat, $106 million.

3.7.3.4 Shuttle reliability is 0.995 and Tug reliability is 0.970. The probability of a successful Navsat deployment or replacement flight is therefore 0.96515. Shuttle intact abort capability is assumed.

3.7.3.5 Refurbishments are costed on the basis of the probability of failure of individual subsystem units and costs of these units. Stated mathematically,

$$C_R = \sum_{i=1}^{i=44} (1 - R_i)\, C_i\, N_i$$

$$C_i = C_s\, W_i$$

$$R_i = e^{-\lambda_i T_R}$$

where C_R = cost to refurbish satellite

i = subscript denoting subsystem unit (the Navsat subsystems are divided into 44 units in this analysis)

R_i = reliability of unit i

C_i = cost of unit i

N_i = number of redundant unit i's

C_s = spacecraft specific cost, \$18,000/lb in this analysis

W_i = weight of unit i

λ_i = failure rate of unit i

T_R = time at which refurbishment occurs.

It will be seen in the above equations that refurbishment cost C_R depends upon the time T_R when refurbishment is accomplished. In the analysis, T_R is varied from one to seven years. Refurbishments also occur after random failures.

The equation for C_R includes only hardware costs. Costs of Navsat ground transportation, handling, and testing during the refurbishment cycle are not included. It is expected that such costs will be introduced into the analysis at the same time that the specific cost concept, symbolized by the use of C_s, is replaced by a more detailed accounting of subsystem element costs. At the present time, it is believed that the \$18,000/lb figure for C_s may be high, partially compensating for omission of the aforementioned non-hardware costs.

3.7.3.6 Depletion of expendables is included in the analysis; wearout failures are excluded. It is planned to include wearout in future analyses.

3.7.3.7 The baseline Navsat has a mean mission duration (MMD) of four years. Designs have also been developed of satellites with MMD's of three and five years as part of this study.

3.7.3.8 Time between satellite failure and fix by deployment of a replacement satellite is a variable in the analysis. Specific time delays chosen are 1/2, 1, and 2 months.

3.7.4 Navsat Availability

As discussed in Section 3.7.3.1, two criteria for Navsat availability have been examined separately:

(1) "Single satellite" availability assumes that the availability of each satellite, independent of the rest, is of interest. This assumption makes the results of the analysis applicable to satellites of communications or meteorological types, for example, rather than to those which are part of an inter-dependent system, such as a navigation satellite system.

(2) "Four satellite" availability assumes that the Navsat system is available when all of the four satellites in the system are operating satisfactorily. When a random failure occurs in any one of the four satellites, the system becomes unavailable until the failed satellite is replaced.

Availability of the Navsat system over a period of time is the ratio of total operating time during the period to the duration of the period. This is written as

$$A = \frac{T_o}{T}$$

where

A = System availability

T_o = Total operating time

T = Duration of time over which availability is to be determined (ten years in this analysis)

T_o would be equal to T except for the fact that random failures occur which can only be remedied after a Shuttle delay time. Availability by the first criterion (single satellite) is calculated in the refurbishment analysis as follows:

$$A = 1 - \left(\frac{E_F}{S}\right)\left(\frac{H}{T}\right)$$

where the symbols are as defined previously plus

E_F = total expected number of random failures (for S satellites)

S = number of satellites in system (four in this analysis)

H = Shuttle delay time (one-half, one, and two months in this analysis).

Availability of the S Navsats considered as an inter-dependent system is calculated in the refurbishment analysis by raising the expression given above to the S power.

In the analysis of Navsat availability using the warning system, satellite availability is expressed by the following:

$$A = 1 - H\left\{ F_A + \frac{F_W - F_A}{2}\left[1 - R_s(H)\right]\right\}^{*}$$

$$F_A = \frac{1 - R_A(T_R)}{M_A(T_R)}$$

$$F_W = \frac{1 - R_W(T_R)}{M_W(T_R)}$$

* Derivation of these are shown in Appendix A.

where H is as defined previously and

$M_A(T_R)$ = MMD of the set of satellite units not included in the warning set at time T_R (the planned refurbishment time)

$M_W(T_R)$ = MMD of the entire satellite at T_R using warning set logic (warning given when last redundant element reached) for the warning set

$R_A(T_R)$ = reliability of the set of satellite units not included in the warning set at T_R

$R_s(H)$ = reliability of the satellite during the interval H using "normal" logic (not warning set logic) for the warning set

$R_W(T_R)$ = reliability of the entire satellite at T_R using warning set logic for the warning set.

The expression for A is raised to the S power when the availability of S satellites is to be determined.

3.7.5 Redundancy Level for Desired Lifetime

The basic Navsat data describes a satellite which has a fixed MMD. That MMD is determined by the reliability of each of the individual "black boxes" in its design, the amount of redundancy of these units, and the maximum lifetime afforded by the satellite expendables.

The Aerospace OPT computer program is capable of taking a basic satellite design with a given MMD and varying that design to achieve any other desired MMD's. The program achieves this objective by varying both the redundancy level and quantity of expendables. The OPT Program has been used with the basic Navsat data, which represents a four year MMD, and has produced alternate designs with MMD's of three and five years.

3.7.6 Black Box Reliability Model

The reliability of each "black box" included in the Navsat design is described by a failure rate, λ_i. The reliability or survival curve is defined by the following exponential:

$$R_i = e^{-\lambda_i t}$$

where: R_i = Reliability of the i'th black box

t = Time at which R_i is being evaluated

The Navsat is composed of 44 types of black boxes. These, and their failure rates, are identified in Table 3-1.

3.7.7 Satellite Reliability Model

The entire reliability model of the Navsat is implicitly included in Table 3-1. For example, Figure 3-2 shows the Telemetry, Tracking and Command (TT&C) subsystem reliability diagram. Table 3-1 shows that the TT&C subsystem includes 11 different types of units. It also shows how many of each of the units are required to provide satellite MMD's of three to five years. How many are required in the warning system examined in the analysis is also shown. This data is reflected in Figure 3-2.

Each of the redundant units shown in Figure 3-2 and those included elsewhere in the Navsat design are in "standby" redundance. They are treated as partly active while in the standby mode. Units in standby redundancy can and do fail, although at lower rates than when active. Their failure rates while in standby redundancy are therefore assumed to be non-zero.

The general expression for the reliability of N redundant units of which only one must be operating for system success (the others in standby redundancy) is as follows:

$$R(N,T) = e^{-\lambda_a T} \sum_{K=1}^{N} \frac{\left[1 - e^{-\lambda_b T}\right]^{K-1} \Gamma(B+K-1)}{\Gamma(K)\;\Gamma(B)}$$

where:

	$R(N,T)$	=	Reliability of the N redundant units
	λ_a	=	Failure rate of active unit
	T	=	Time at which reliability is being evaluated
	K	=	Summation variable over all redundant units
	λ_b	=	Failure rate of unit in standby redundancy, less than λ_a
	Γ	=	Symbol for the gamma function
	B	=	Ratio of λ_b to λ_a (0.1 in the Navsat analysis)

The expression given above is used with each of the types of redundant units shown in Figure 3-2 to derive the reliabilities of each of the redundant sets. These are then used in standard reliability multiplication fashion to produce the reliability of the TT&C subsystem.

Finally, the reliabilities of each of the subsystems are multiplied together to produce the Navsat reliability.

3.7.8 Satellite Reliability

Reliabilities of the four Navsat systems represented by Table 3-1 have been determined for periods ranging up to seven years. Expendables have been increased in each case to allow reaching that seven year point. Results are shown in Figure 3-3.

Increasing the expendables of a satellite increases its MMD. This occurs even when the design is otherwise unchanged in terms of subsystem reliabilities and redundancy. Thus, the lower three reliability curves of Figure 3-3 can be integrated out to the seven year point to show MMD's greater than the indicated three, four, and five years. Expendable depletion points for the three, four, and five year MMD optimal designs are less than seven years.

3.7.9 Random Failures

The failures assumed to occur in the Navsat in this analysis are random failures. They are equally likely to occur at any time in the operating life of the satellite. Non-random failures are those due to such phenomena as wearout.

For a satellite which is refurbished and reused, the number of random failures experienced by a satellite over the duration of a satellite program is influenced by the refurbishment schedule.

The following equation is used for a single satellite:

$$E_R = \left[1 - R_s(T_R)\right] \frac{T_P}{M_s(T_R)}$$

where

E_R = expected number of random failures during the program

$R_s(T_R)$ = probability of a single satellite surviving to T_R

T_R = refurbishment time

$M_s(T_R)$ = MMD associated with T_R

T_P = program length.

When the expected number of failures of S satellites is required, the above expression for E_R is multiplied by S.

When the warning system is used, the expression for the expected number of unscheduled refurbishment flights changes slightly. The expression becomes

$$E_R = \left[1 - R_W(T_R)\right] \frac{T_P}{M_W(T_R)}$$

$R_W(T_R)$ and $M_W(T_R)$ are as defined in 3.7.4. Again, when S satellites are involved, the expression for E_R is multiplied by S.

3.8 NAVSAT ANALYSIS RESULTS

Two basic strategies for maintaining the Navsat system have been analyzed, and the results are provided herein. The first strategy has been described in 3.7.1. The results of using this basic strategy, modified in detail by changing the refurbishment interval, are given in 3.8.1 through 3.8.3. Results of using the warning system described in 3.7.2 are also included in 3.8.1 through 3.8.3.

3.8.1 Availability vs Refurbishment Interval

Availability versus refurbishment interval for a single Navsat is shown in Figure 3-4. Parameters in the figure are satellite redundancy level (represented by the three satellite designs whose nominal MMD's are three, four, and five years), use of the warning system, and Shuttle delay time.

It is immediately obvious that the impacts of Shuttle delay and satellite refurbishment interval are considerably reduced by use of the warning system.

It appears in Figure 3-4 that only the warning system can provide the high availabilities desired unless both short Shuttle delay and frequent refurbishment are obtained. This conclusion cannot be reached, however, until further analysis, soon to be completed, proves or disproves its validity. The reason for the uncertainty at this point is that Figure 3-4 does not show a true comparison between periodic refurbishment and periodic refurbishment plus warning. This is because the best satellite in the refurbishment analysis is one with redundancy for a five-year MMD, while the satellite in the warning analysis has a greater MMD because it has had much redundancy added to the five-year design. The added redundancy can be observed in Table 3-1.

Figure 3-5 shows availability versus refurbishment interval for a Shuttle delay of one month. As expected, these curves fall between those for delays of one-half month and two months shown in Figure 3-4.

It is helpful in reviewing this data to use the relationship that an availability of 0.999 is equivalent to an average down time of about nine hours per year. Over a ten year period, this amounts to about four days. Since even a single random failure results in a down time equal to the Shuttle delay, two weeks minimum in the analysis, the interpretation of the high availabilities exhibited here is that the probability of even a single failure is very low.

3.8.2 Program Cost vs Refurbishment Interval

Program cost is shown in Figure 3-6 as a function of refurbishment interval. Three levels of satellite redundancy and use of the warning system are represented. This figure shows that the highest availabilities plotted in Figures 3-4 and 3-5 are attained at substantial increases in program cost over those for the lower availabilities. The figure also shows that Navsat program costs vary inversely with the level of basic satellite redundancy. This latter conclusion does not necessarily apply to other satellites. Program costs for the warning system case are higher than for the refurbishment cases because more satellite replacement flights must be made and because satellite costs are higher.

3.8.3 Minimum Program Cost vs Availability

A restricted representation of minimum program cost versus availability is shown in Figure 3-7. The restriction is that results are limited to the system maintenance strategies examined in this analysis (described in 3.7.1 and 3.7.2).

The curve representing a Shuttle delay of one-half month is seen to be the best of the minima. It is assumed for this figure that Shuttle delay cannot yet be accurately predicted, that the delay ultimately realized will be a function of the size of the Shuttle fleet, number of launch sites, Shuttle design, launch complex design, and other factors. Therefore, all three curves are shown. Each curve is for the five year MMD satellite design, modified in the warning analysis by addition of greater redundancy.

D

As noted in 3.8.1, it is not intended that results shown in this section be considered a direct comparison between periodic refurbishment and periodic refurbishment plus warning. Such a comparison will be possible when the needed additional data is available.

Figure 3-7 does show, however, accurate representations of program costs versus availability for the satellites and strategies studied. In the area of cost overlap between the two sets of data, the warning system is decidedly superior. The superiority comes partly from the use of warnings and partly from the greater satellite reliability.

Figure 3-8 is the first figure in this section to show results for the case in which all four Navsats must be operating satisfactorily for the system to be available. Results are similar to those of Figure 3-7.

3.9 INTELSAT IV ANALYSIS STATUS

The Intelsat IV analysis has not progressed as far as the Navsat analysis. This is because of difficulties in obtaining the required data in a timely manner.

3.9.1 Reliability and Weight Data

Reference 3-1 contains reliability diagrams and other reliability data sufficient to define the reliability of the basic Intelsat IV. Reference 3-2 contains detailed weight data.

3.9.2 Weights for Individual Units

The reliability diagrams of Reference 3-1 show the units into which the Intelsat IV subsystems have been divided for purposes of estimating reliability. The detailed weight data of Reference 3-2 has been correlated with the reliability data to produce the weight of each unit. This unit/weight data will be used by the Aerospace OPT computer program to produce optimal designs for desired MMD's.

3.9.3 Work to be Completed

The weight and reliability data will be fed into the OPT program to produce optimal Intelsat IV designs for a range of MMD's. Selected designs, analogous to the three selected for Navsat, will be analyzed to determine minimum program cost versus availability. It is planned to introduce new facets to the analysis such as the effects of wearout.

3.10 NIMBUS-B ANALYSIS STATUS

The Nimbus-B analysis has made less progress than that for the Intelsat IV. Again, difficulties in acquiring sufficiently accurate data have occurred.

3.10.1 Reliability and Weight Data

Reference 3-3 includes the Nimbus-B weight data which has been acquired to date. The data is less detailed than required. Efforts to obtain the appropriate level of detail have thus far been unsuccessful. Reference 3-4 contains Nimbus-B reliability data.

3.10.2 Work to be Completed

When the required detailed weight data is obtained, it will be correlated with the reliability data. This will result in weights for each of the units in the Nimbus-B reliability model. At this point, the Nimbus-B analysis will have advanced to the present state of the Intelsat IV analysis. Progress beyond this point will be the same for each of the two satellites and is described in section 3.9.3 above.

3.11 OBSERVATIONS

The first results of the low risk analysis indicate that using failure warnings may significantly enhance availability compared to the technique of responding only to satellite outages between refurbishment intervals.

These analyses show that an availability of 0.999 is predicted at a reasonable cost with a simulated Space Shuttle supported satellite system. Down time would thus average 9 hours per year or less for a single satellite, exceeding by orders of magnitude predictions of availability for current satellites. Although the satellite availability is significantly affected by Shuttle delay time (see Figures 3-7 and 3-8), the effect is less serious with the "warning" maintenance strategy than without it. Thus "warning" desensitizes the predicted availability effects of Shuttle delay. The example demonstrates that the risk associated with obtaining dependable system operation can be low with the Space Shuttle. The sensitivity of system availability and dependability to such items as satellite component reliability will be demonstrated by further analyses in the near future.

The potential for trading system costs for availability is also demonstrated (see Figure 3-8). More work needs to be done in order to understand these trades, for example:

1. The effects of increases in redundancy level utilizing the "warning" strategy are being analyzed to study reduced system costs and high availability.

2. The sensitivity of costs and availability to component failure rate needs to be investigated to relate the costs to the risk of satellite component reliabilities which may fall below these specifications.

3. It is planned that the analysis be expanded to include:

   (a) Additional typical satellites (Nimbus, Intelsat IV)

   (b) Redundant satellites on-orbit

   (c) Comparison with ground systems as discussed in this Section.

The results to date using the maintenance strategy with "warning" are very encouraging and form an initial base for establishing principles of low risk operation and applying these principles to specific programs.

3.12 REFERENCES

3-1. Communications Satellite Corporation Technical Memorandum SED-9-70, "Intelsat IV Reliability Analysis and Failure Simulation," 1 October 1970

3-2. "Intelsat IV Third Quarterly Progress and Status Report," Hughes Aircraft Company, Space Systems Division, July 1969

3-3. General Electric Company, Missile and Space Division, Program Information Request/Release, "Nimbus 'B' Weight and Balance, November 1967," dated 9 November 1967

3-4. Operations Research Incorporated Technical Report 469, "Summary Document, Nimbus B Reliability Assessments and Failure Mode Analysis," 12 February 1968

Table 3-1. Navsat Failure Rates and Redundancy

CHARACTERISTIC	CONFIGURATION / CONTRACTOR	TWO STAGE-FULLY REUSABLE					
	CONTRACTOR	MDAC		NR (Two Eng. Orb.)		NR (3 Eng. Orb.)	
	GLOW	4,608,961		5,047,327		4,479,313	
	Element	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter
WEIGHT (lb.)	GLOW	3,755,553	853,408	4,188,223	859,104	3,113,577	1,365,736
	Dry (1)	576,000	221,866	626,933	223,431	480,325	292,626
	Structure Factor	0.191	0.310	0.193	0.294	0.181	0.244
	External Tank Inert (Ea.)	-	-	-	-	-	-
DIMENSIONS	Length (Ft.)	281.7	174.7	268.5	206.2	227.3	231.6
	Span (Ft.)	166.0	107.5	143.5	107	130.8	116.6
	Height (Ft.)	61.0 (2)	63.7 (3)	102 (3)	60.8 (3)	92 (3)	75 (3)
	Total Wetted Area-Ft^2	39,044	22,069	44,756	22,743	NA	NA
	Body Encl. Vol. - Ft.^{3}	209,398	76,095	265,257	108,528	172,142	116,097
PROPULSION	Main Eng No/Thrust Ea.	12/550K (SL)	2/632K (Vac.)	12/550K (SL)	2/632K (Vac.)	12/480K (SL)	3/551K (Vac.)
	OMS No/Type	-	2/RL-10	-	3 @ 10K	-	3 @ 10K
	ACPS - No.	16	30	30	29	NA	NA
	ABES Type/No.	F101/F12B-3/10	F101/F12B-3/4	JTF22A-4/12	JTF22A-4/4	NA	NA
B/O RELATIVE STAGING VELOCITY(FPS)		11,026		10,832		7,235	
REF. FIGURE		4-8		4-9		NA	

(1) Excludes Drop Tanks
(2) From Static Ground Line to Top of Vertical Stabilizer
(3) From Bottom of Fuselage to Top of Vertical Stabilizer

Table 3-1. Navsat Failure Rates and Redundancy (Cont'd)

SUBSYSTEM	UNIT	FAILURE RATE (λ), FAILURES PER HOUR, A X 10^{-B}		NUMBER OF UNITS			
		A	B	3 YR MMD	4 YR MMD	5 YR MMD	WARNING
ELEC INTEGRATION ASSY	ELECTRONIC SEQUENCER	5.00	11	1	1	1	1
	COMMAND PROC - 2ND LEVEL GATES	1.03	6	1	2	2	2
	COMMAND CIRCUITS	6.15	7	1	1	2	2
ELECTRICAL POWER	SOLAR PADDLE	2.00	8	2	2	2	3
	SHUNT ELEMENT	2.10	7	2	2	2	3
	PCU	2.62	7	1	1	1	1
	BATTERY	6.60	6	3	3	3	3
	MSS CONVERTER	4.36	6	2	2	2	3
	PAYLOAD CONVERTER	5.22	6	2	2	2	3
ATTITUDE CONTROL ASSY	SUN SENSOR ASSY	1.50	6	2	2	2	3
	RATE GYRO ASSY	3.32	9	1	1	1	1
	GYRO AUX ELECTRONICS	3.03	10	1	1	1	1
	TLM CONDITIONING ELECTRONICS	5.69	6	2	3	3	3
	MODE SW ELECTRONICS	4.99	6	2	2	3	3
	MODULATING PULSE ELECTRONICS	8.88	6	2	3	3	3
	YAW REACTION WHEEL ELECTRONICS	1.23	6	2	2	2	3
	ARRAY DRIVE ELECTRONICS	3.03	6	2	2	2	3
	YAW REACTION WHEEL	6.40	8	1	1	1	1
	PNEUMATIC ASSY	3.49	7	1	1	1	1
	PITCH/ROLL RW + ELECTRONICS	2.65	6	1	1	2	2
	EARTH SENSOR ASSY ELECTRONICS	1.41	6	1	2	2	2
	EARTH SENSOR (HEAD ASSY)	2.12	6	4	5	5	5

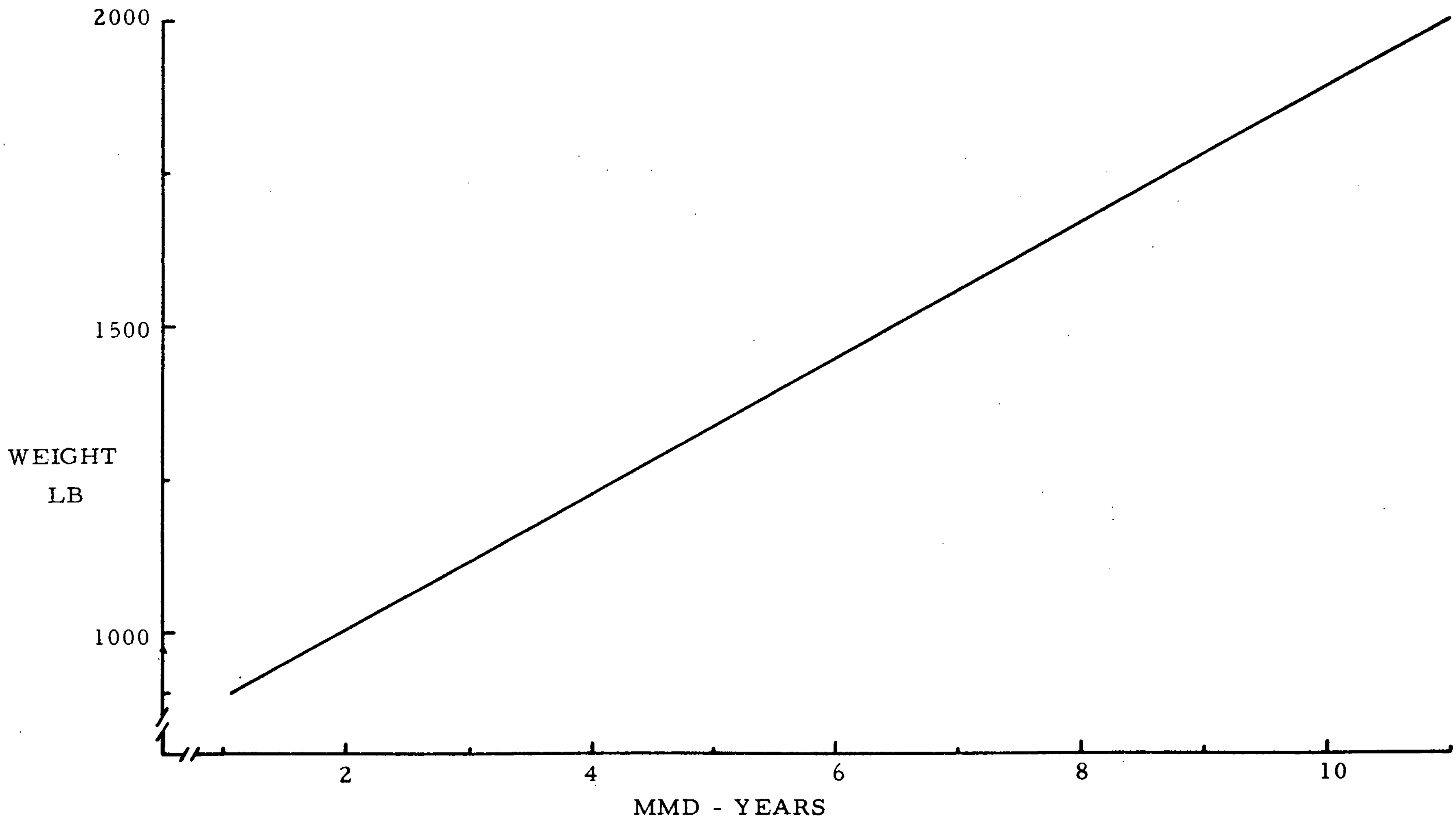


Figure 3-1. Navsat Weight vs MMD

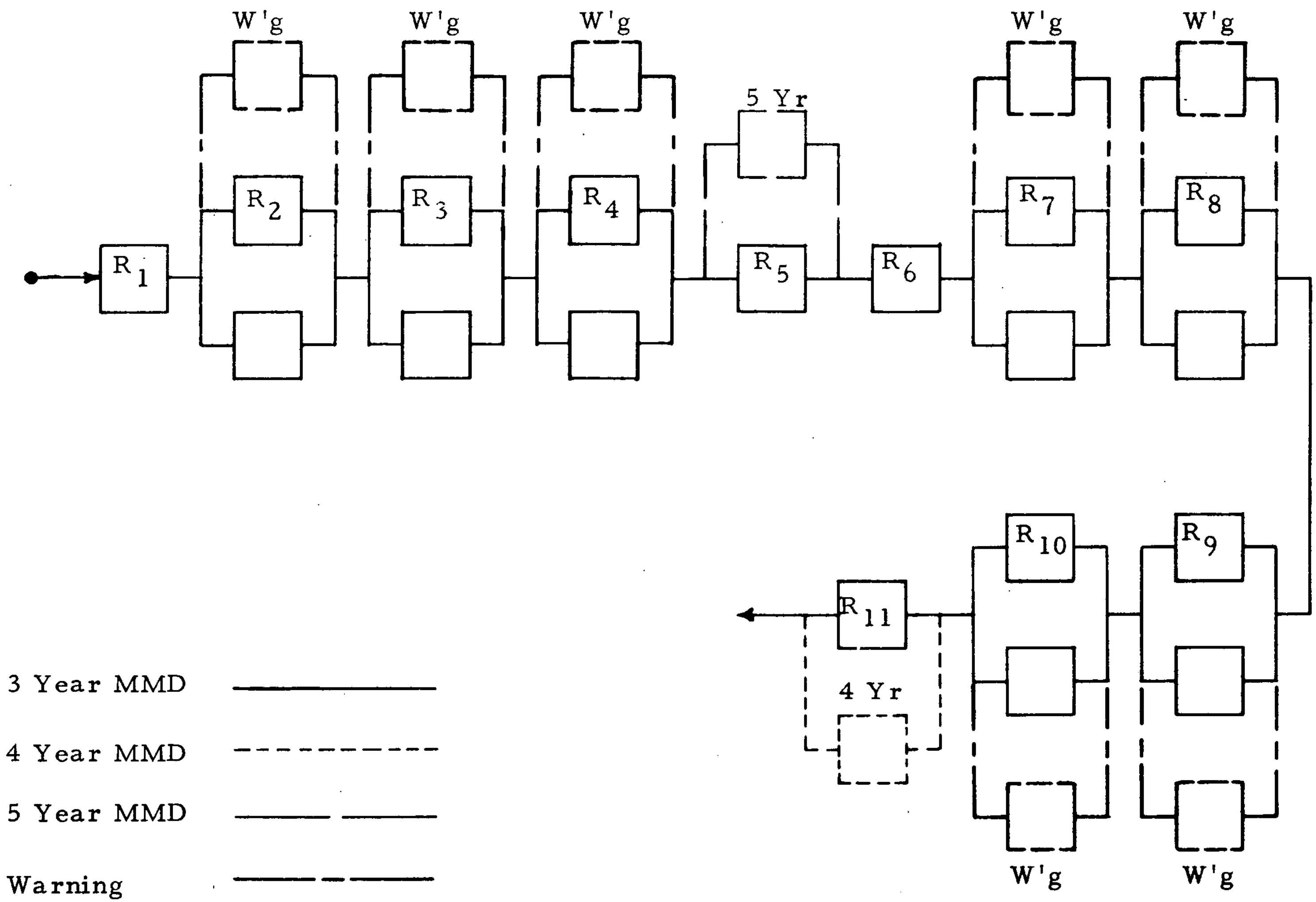


Figure 3-2. TT&C Subsystem Reliability Diagram

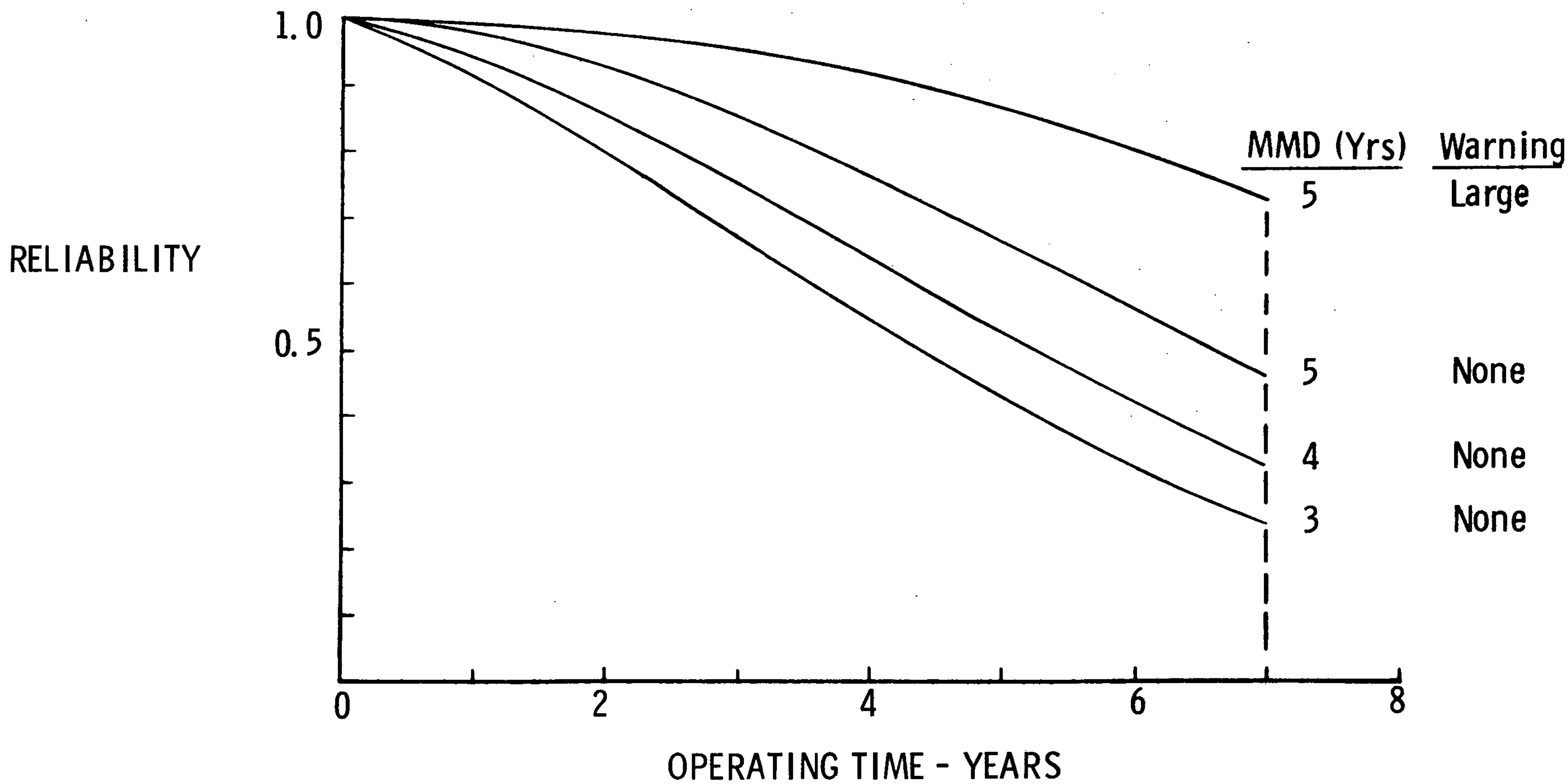


Figure 3-3. Reliability Curves for Navsats

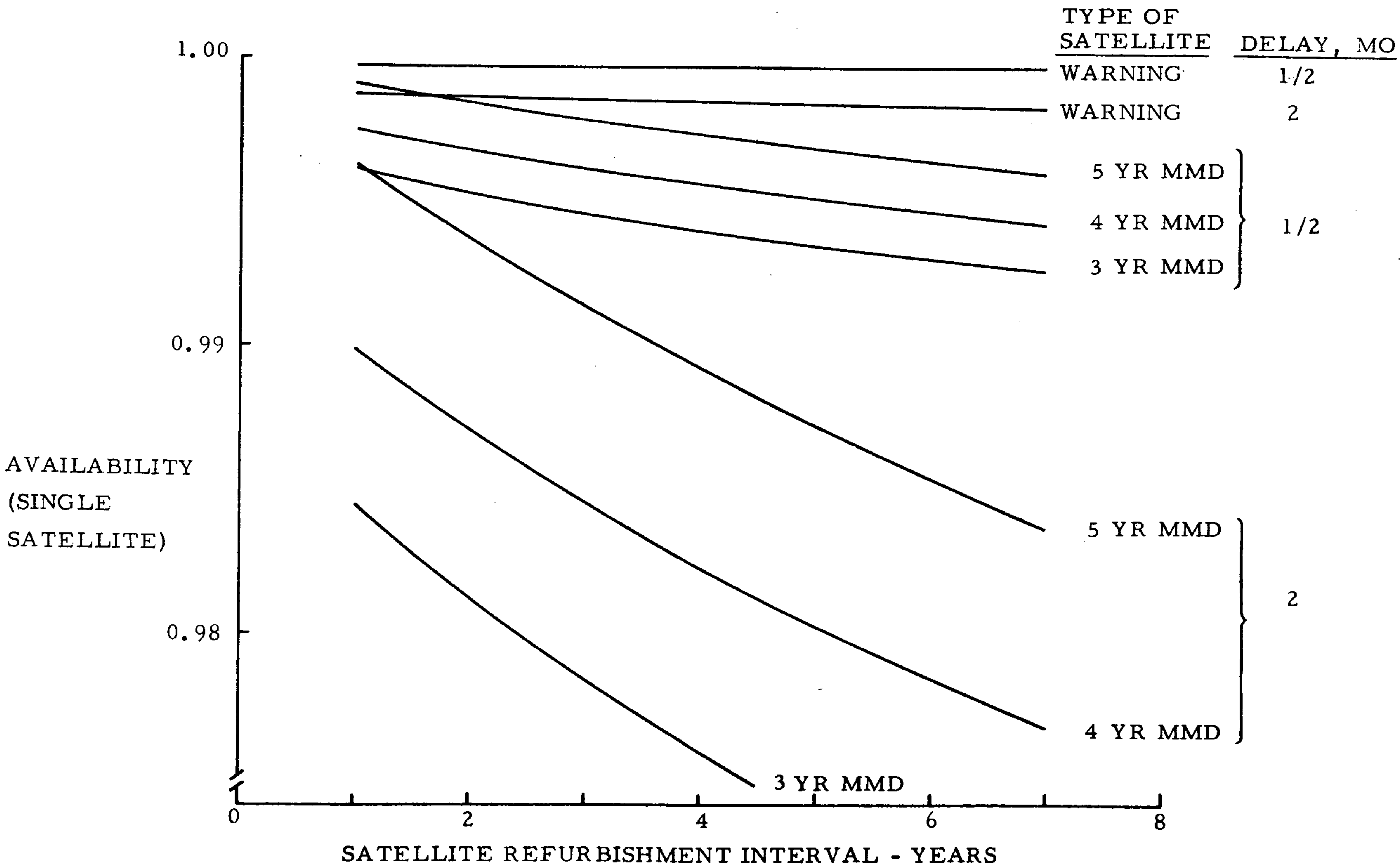


Figure 3-4. Navsat Availability vs Refurbishment Interval

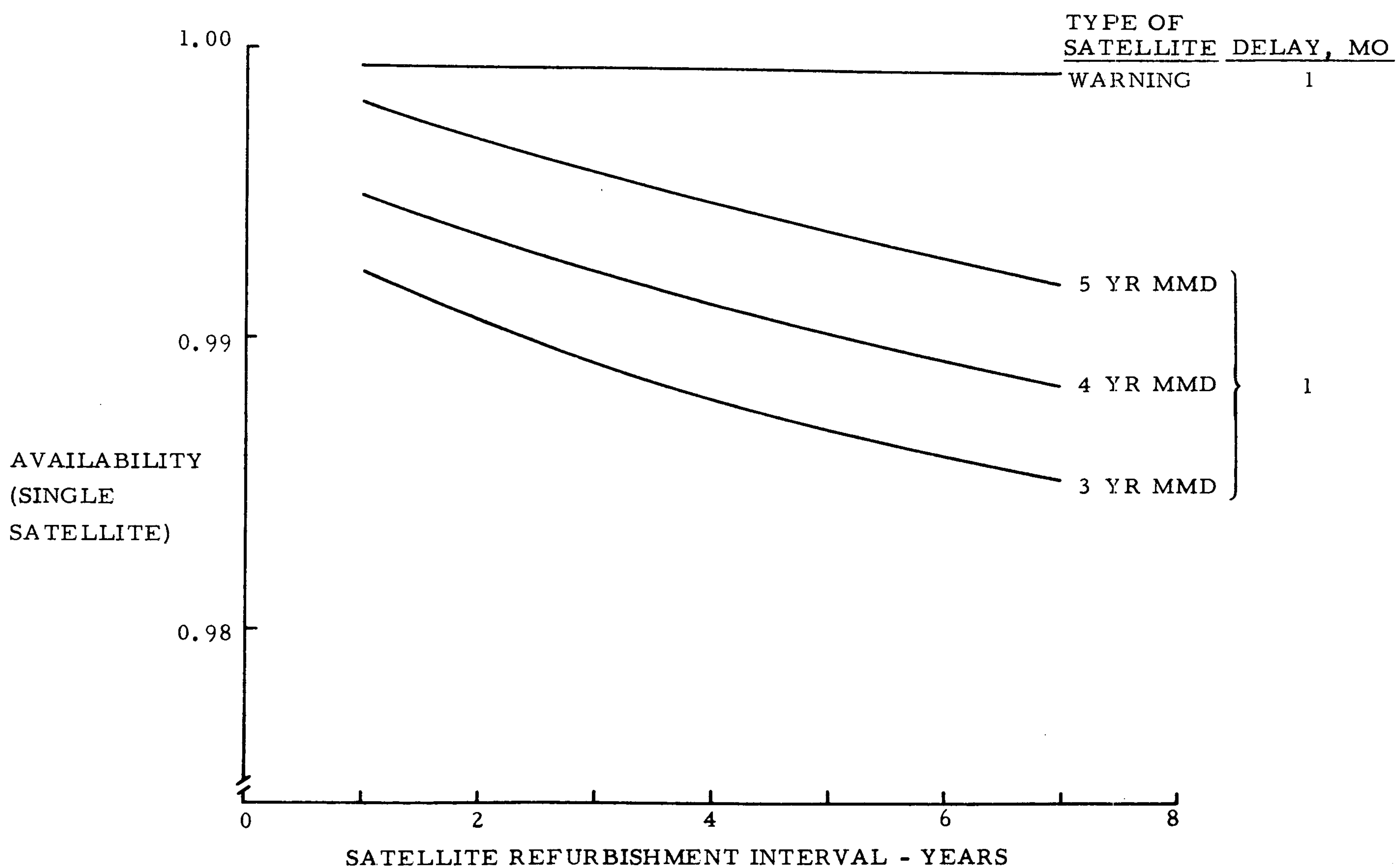
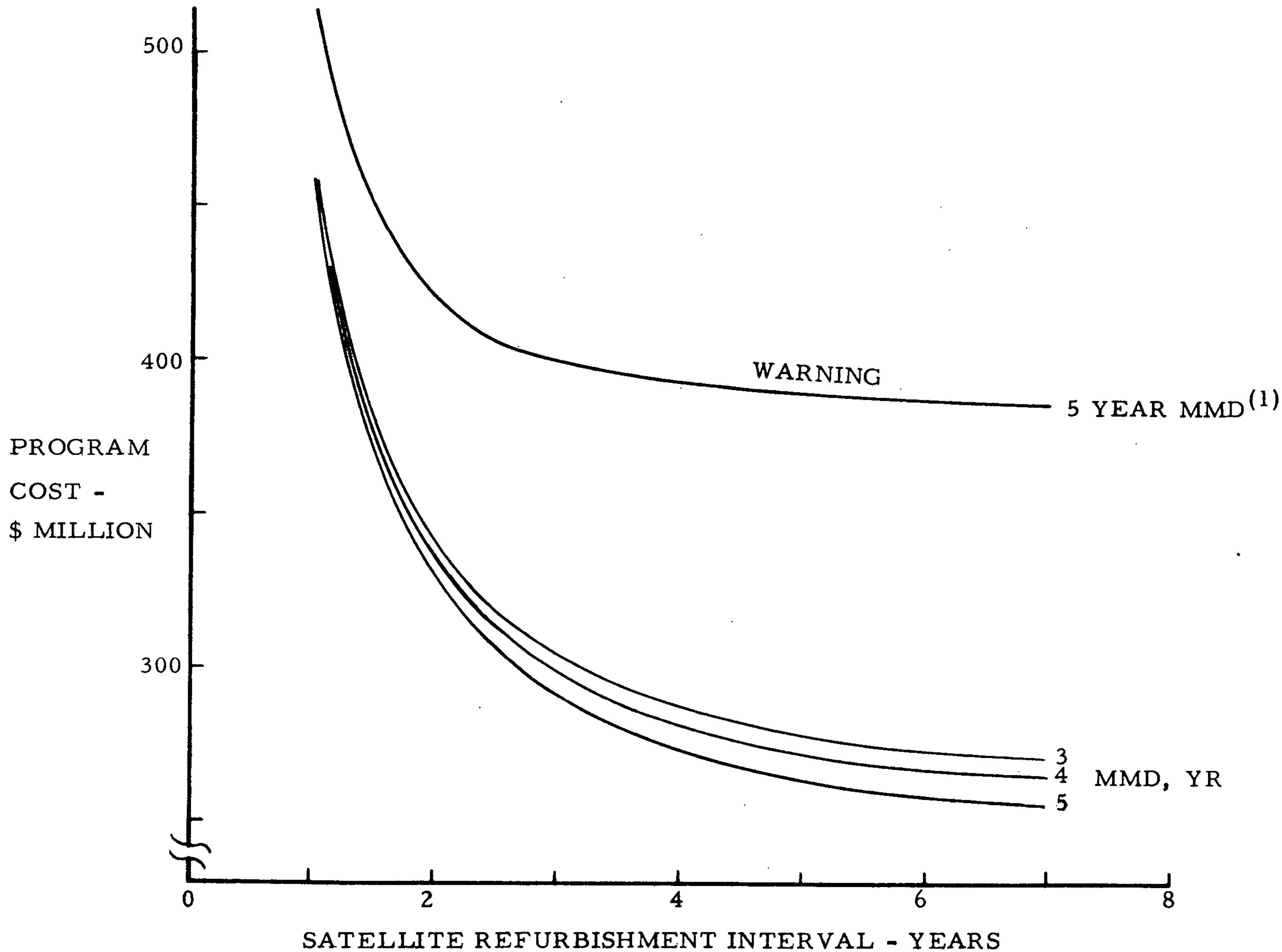


Figure 3-5. Navsat Availability vs Refurbishment Interval



(1) See Section 3.7.2 for Satellite Modification Description

Figure 3-6. Navsat Program Cost Versus Refurbishment Interval

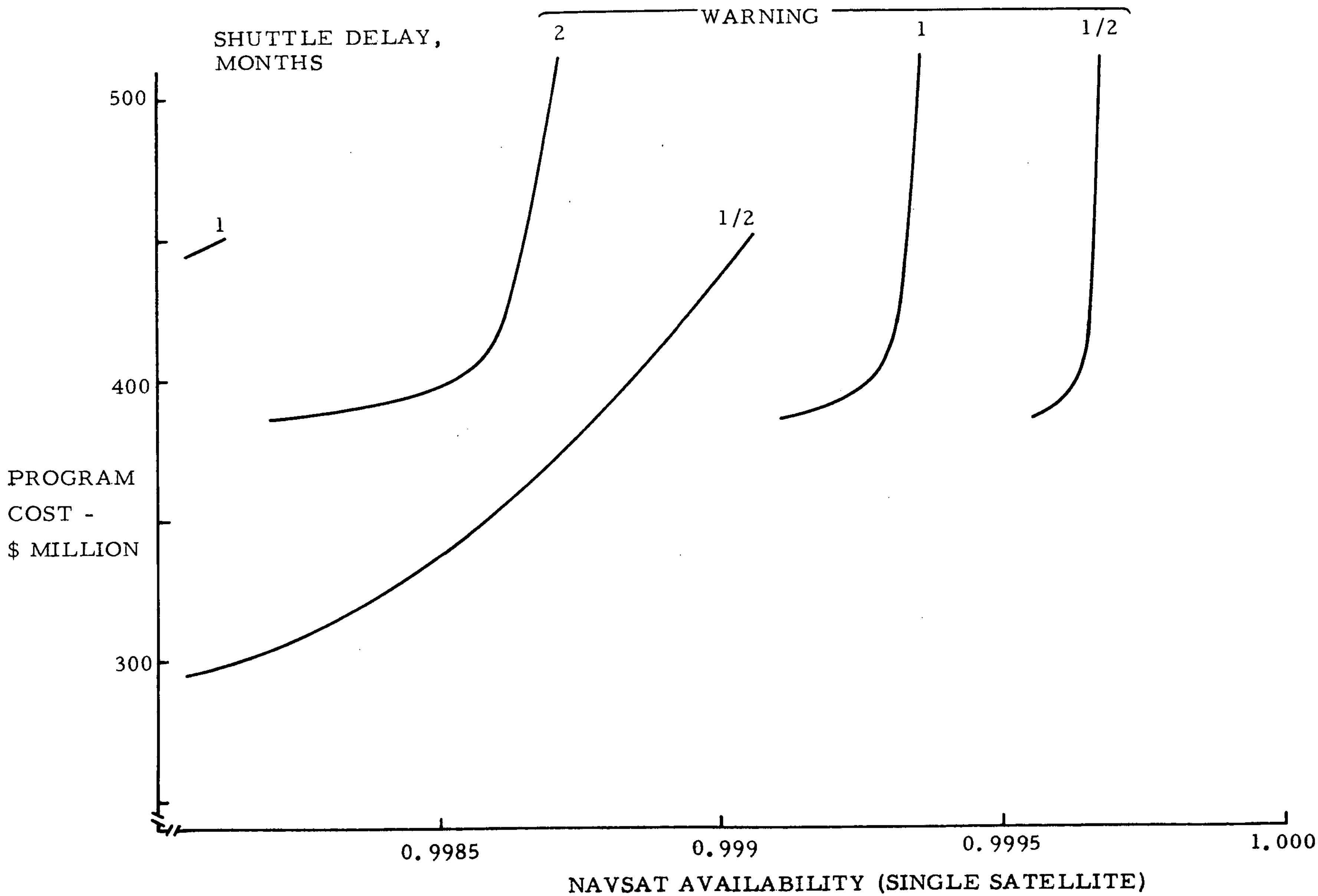


Figure 3-7. Navsat Program Cost vs Satellite Availability

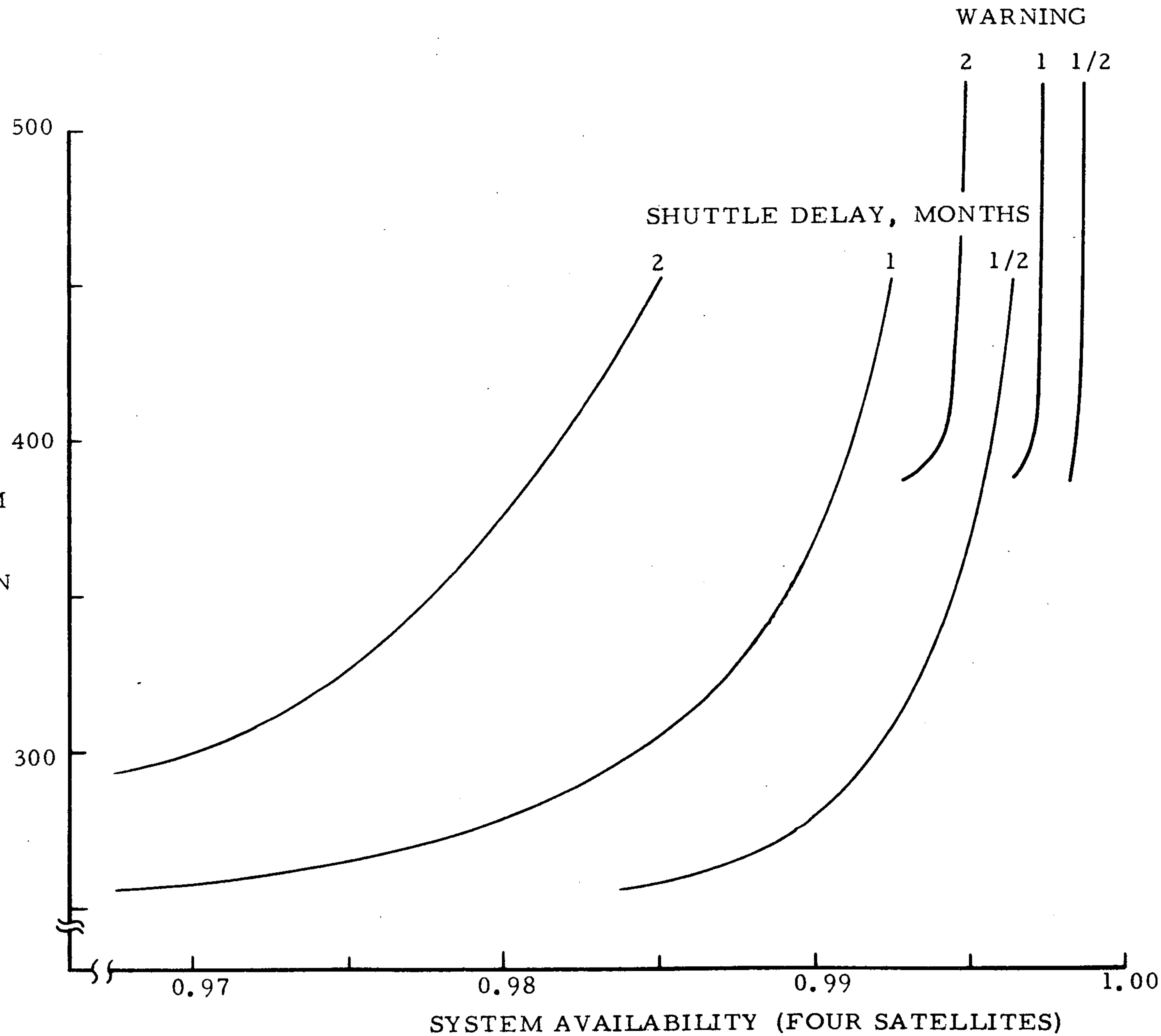


Figure 3-8 Navsat Program Cost vs System Availability

4. REUSABLE LAUNCH SYSTEMS

Major launch systems activities during the Integrated Fleet Analysis study extension period were focused on the review of NASA Phase A/B Space Shuttle final reports, and the monitoring of the Phase B study extensions through liaison with the contractors and NASA centers. The purposes of these activities were to collect and assimilate Space Shuttle design and performance information and to update system definitions as required to support capture, costing, and equal risk program analyses. Summary results of these investigations along with additional data analyses and reformatted information not included in the Study A final report (Reference 4-1) are documented below.

Section 4.1 presents Space Shuttle Phase B study weight trend comparisons and a Shuttle weight growth projection for cost dispersion estimation purposes. Most of this information was reported in the Study A June 1971 Technical Monitoring/Interchange meeting, but was not documented in the final report. Summary comparisons of the FY 71 NASA Phase A/B Space Shuttle systems studies designs and a synopsis of the four month study extension results are given in Section 4.2. Performance characteristics for the Space Shuttle two stage internal tank design and two stage design with orbiter external LH_2 tanks (OET) are reported in Section 4.3.

4.1 SPACE SHUTTLE WEIGHT TRENDS AND WEIGHT GROWTH PROJECTIONS

4.1.1 Phase B Study Weight Trends

Phase B shuttle weight trends were presented in the final report (Reference 4-1) for variations in MDAC high crossrange design through March 1971. Figures 4-1, 4-2, and 4-3 present this same weight trend data extended through the June 1971 time period to reflect the Phase B final design. Comparisons of the NR and MDAC Phase B booster and orbiter dry weight and structure factor trends are given in Figures 4-4 and 4-5, respectively. The calendar time variation in Space Shuttle program major design guidelines is illustrated in Figure 4-6 for information and orientation purposes. Major increases in booster and orbiter weights are shown to occur in late 1970 when the ABES fuel was changed from LH_2 to JP-4 and in early 1971 when new Level I design requirements were implemented. Booster weight variations during the Phase B study are shown to have been more severe than those in the orbiter.

The NR and MDAC Phase B Shuttle weight trends for the booster and orbiter designs (Figures 4-4 and 4-5, respectively) show similar dry weight and structure factor trend patterns with the final weight of both elements being slightly higher for the NR design. However, while the final booster structure factors are very close, there is a significant difference in structure factor values for the orbiter. Since the gross and dry weights of the two designs are very close and the payload weight is the same, the structure factor difference must be due to a combination of small differences in a number of parameters including residual propellants and fluids.

4.1.2 Weight Growth Projections for Cost Dispersion Analyses

NASA guidelines required the contractors to include a 10 percent growth allowance in the Phase B Space Shuttle design dry weights, less GFE propulsion engines, to provide a margin for expected weight growth during Shuttle design development. Contractor analyses (Reference 4-2) utilizing weight history data for a number of previous aerospace projects concluded that a 10 percent growth allowance would have provided a 90 percent probability of achieving program weight goals, excluding weight growth due to changes in customer requirements (which on the average accounted for about one-half of the total weight growth).

The Aerospace Corporation reviewed the contractor weight growth analyses and utilized this information, in conjunction with in-house weight history data and experience, to make independent Space Shuttle weight growth projections for use in cost dispersion analyses. Projected weight growth from April 1971 to first manned orbital flight for the three major structural weight related costing sub-groups is listed in Table 4-1 along with the baseline weights.

Figure 4-7 is a graphical presentation of the Shuttle weight growth projections. Costs of other subsystems such as engines, avionics, ECLS, etc are not weight dependent to the same extent as the three structurally related subgroups noted above, and are not included in this weight projection.

The MDAC April 1971 Mass Properties Status Report (Reference 4-3) indicated a booster growth allowance of only 5.6 percent. The first step in predicting total weight growth for costing purposes was to resize the booster to include the required 10 percent growth allowance. This resizing was accomplished on the Aerospace Mass Properties Vehicle Synthesis Program (Reference 4-4). The orbiter weight included the required 10 percent growth allowance and was therefore not resized. Baseline and 10 percent growth allowance weights are listed in Table 4-1 for each of three subgroups.

The predicted weights listed in Table 4-1 were determined by applying a growth increment to each area based upon Aerospace "best judgment" after a careful review of the design, reported detail weights and contingencies, and degree of current state-of-the-art employed in each of the included subsystems. These predicted subgroup weights are intended for use in Shuttle cost dispersion analyses and not as an indicator of actual Shuttle design or performance characteristics. In arriving at the predicted weights, the Shuttle system was not resized above the 10 percent growth allowance point in order to maintain constant payload performance capability. An implicit assumption is that when the Shuttle system weight increase exceeded the original 10 percent growth allowance, performance improvements, design/material changes, and additional weight reduction procedures would be instituted with increases in subsystem complexity and cost. The predicted weights are intended to be an indicator of these expected cost increases. It should be noted that the projections do not include weight changes due to revisions in customer requirements.

4.2 SPACE SHUTTLE SYSTEM STUDIES

4.2.1 Phase A/B Studies

The Space Shuttle is an advanced space transportation system which is intended to transport passengers, cargo, satellites, propulsion stages, etc. economically and efficiently between the earth's surface and low earth orbit. During

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fiscal year 1971 teams of companies headed by McDonnell Douglas and North American Rockwell were under contract to the NASA to conduct 12 month Phase B system studies of the shuttle. Parallel to this Phase B activity, other contractor teams (principally Grumman/Boeing and Lockheed) were funded by NASA to conduct Phase A studies of alternate Space Shuttle concepts. In addition, the USAF Space and Missile Systems Organization funded the two NASA Phase B Shuttle study contractors to conduct independent DoD Space Shuttle impact studies. Table 4-2 presents a matrix of the Phase A/B studies and lists the Space Shuttle concepts studied by each of the principal contractor teams during FY 1971.

The original objectives of the NASA Phase B studies were to analyze and provide a preliminary design of a completely reusable two stage Space Shuttle which met the established program goals and was supported by traceable, substantiating data in areas vital to the feasibility of the system. Beginning in April 1971 design emphasis in the Phase B studies was shifted from a completely reusable system to analysis of an orbiter with external expendable hydrogen tanks. The DoD impact studies involved the assessment of the capability of the fully reusable Phase B Space Shuttle for the accomplishment of DoD missions and the identification of DoD Shuttle System modifications and associated costs.

The Phase A studies were concerned with alternate Space Shuttle concepts and the primary issue addressed was: is there a lower cost shuttle option than the fully reusable system?

At the initiation of FY 71 study efforts, NASA defined major shuttle system requirements (Level I) for use by the Phase B contractors. The Phase A study contractors proceeded with alternate Space Shuttle concept definitions. These Level I requirements were modified during the course of the Phase A/B studies. Figure 4-6 presents a chronology of the changes in major system requirements during the course of these study efforts.

Contractor Study Results

Space Shuttle vehicle designs resulting from the FY 71 NASA contractor studies are presented in Figures 4-8 through 4-14 as noted below:

Configuration	Contractor	Figure
Two Stage Fully Reusable	MDAC	4-8
	NR	4-9
	GAC/BAC	4-10
Drop Tank Orbiter-FR B/O	MDAC	4-11
	NR	4-12
	GAC/BAC	4-13
Stage and One-Half	LMSC	4-14

Table 4-3, "NASA Phase A/B Vehicle Summary," presents a matrix of characteristics of the vehicle concepts as reported by the contractors at the conclusion of the Phase A/B studies. Pertinent information such as weight, structure factor, vehicle dimensions, wetted area, enclosed volume, propulsion systems and number of engines, etc., are presented for comparative purposes.

It should be noted that the Space Shuttle system baselined in the Integrated Fleet Analysis final report (Reference 4-1) is generally similar in design and characteristics to the final MDAC two stage fully reusable design. Thus only small cost differences would be expected between the contractor's final design and that utilized for Study A costing. Moreover, since the performance characteristics of the two designs are essentially the same, the Study A STS final capture analysis would not be affected.

Table 4-4 presents a summary comparison of the detailed weights reported by the contractors for the final two stage fully reusable and orbiter external tank design. Significant differences may be noted in the contractor detailed weights for the various subsystem areas. This may be partially due to the fact that the MDAC and NR teams concentrated on the fully reusable designs for most of the Phase B study and only spent a few months addressing the external tank orbiter system. On the other hand, the GAC team largely considered the fully reusable vehicle in a parametric fashion and focused most of the detailed design work on the external tank orbiter system. It should be noted that toward the end of the Phase B studies the NASA center teams placed most of their emphasis on the drop tank orbiter systems.

4.2.2 Four Month Shuttle Study Extensions

On 1 July 1971, NASA extended the Space Shuttle contractor studies (with the exception of Chrysler Corporation) for an additional four month period. These studies were to address the feasibility of various expendable first stages for use with a reusable orbiter as an interim step in a phased development program ultimate leading to a fully reusable two stage system. The objective was to keep the annual peak funding to an acceptable level (~ $1 Billion per year) while still maintaining interim manned spaceflight. A matrix of some of the various contractor configurations studied during this extension period is presented in Table 4-5. Figure 4-15 illustrates several of the configurations studied by the contractors. Some of the key issues and guidelines for this interim study phase are as follows:

(1) Use established Level I and II requirements.

(2) Use previous NASA and contractor study results.

(3) Place study emphasis on:

a. Effects of expendable tanks on vehicle size/cost (LH_2 or LO_2/LH_2)

b. Sensitivity of vehicle costs to payload size and weight

c. Utilization of interim launch vehicles (3 per year)

d. Definition of schedules, costs, and programmatic aspects of candidate systems

e. Establish evolution feasibility and flow for ultimate reusable system

f. Landed weight of 45K payloads is 25K and of 65K payloads is 40K

g. All 40-foot payload bay cases shall be stretchable to 60 feet

For the first two months of the extension phase, each of the contractor teams studied the concepts assigned by NASA as noted in Table 4-5. In mid-September the shuttle program was redirected for the final seven weeks of this four-month interim study period. The recent redirection defines a minimum technology program with the following primary ground rules:

Program - Two Alternatives

(1) Concurrent orbiter and booster development with reusable orbiter and reusable LO_2/RP booster (Mark I/II approach).

(2) Phased booster and orbiter development - S-IC flown for five years as an interim expendable booster at a rate of three flights per year. Reusable booster (LO_2/RP) developed after five years.

Schedule

(1) Concurrent Program

a. Orbiter first horizontal flight - June 1976

b. First manned orbital flight - September 1978

c. Operational shuttle - Mark I - September 1978
Mark II - September 1984

(2) Phased Program

a. Orbiter first horizontal flight - June 1976

b. First manned orbital flight using expendable S-1C - September 1978

c. First manned flight with reusable S-1C - September 1983

d. Operational shuttle - September 1984

Requirements

(1) Abort to orbit not required/intact abort is a goal

(2) FO-FO-FS not required

(3) Turnaround time during Mark I usage relaxed to approximately one month.

(4) Staging velocity 6000 fps ± 1000 fps

(5) No go-around capability on orbiter (ABES in payload bay)

(6) Mark II orbiter crossrange 1100 n mi

(7) Max Q - 650 psf

(8) Orbiter payload bay - 15 ft x 60 ft

(9) Crew size of four with a 14.7 psi cabin pressurization

(10) Contractors are to run horizontal flight test program. Government will phase into test program during vertical flight test year.

(11) 40 K polar payload for Mark II orbiter; 10 K polar payload minimum acceptable for Mark I orbiter.

Table 4-6 presents the primary subsystem technology assumptions to be used for the remaining seven weeks of this interim study phase. Table 4-7 delineates the contractor team efforts and areas of concentration for this period.

4.3 SPACE SHUTTLE PERFORMANCE CAPABILITY

4.3.1 Two Stage Internal Tank Design

Space Shuttle performance characteristics utilized in the Integrated Fleet Analysis are documented in the Final Report (Reference 4-1), and correspond to the capability of the McDonnell Douglas two stage, fully reusable design (with internal tanks) of March 1971. The contractor's final design, while differing slightly in terms of mass properties from the interim design, offers essentially the same performance characteristics. The two stage shuttle performance capabilities from the Final Report (Reference 4-1) are repeated in Figures 4-16 and 4-17 for information purposes, and correspond to the maximum achieved with parallel burn of the OMS system during ascent.

Figure 4-16 presents the maximum insertion payload capability (orbiter ABES in) the baseline shuttle can deliver to a 50 x 100 n mi orbit as a function of total mission on-orbit delta velocity available in the vehicle for the NASA Level I design and reference missions. A 20, 300 lb increment of payload growth capability can be achieved, where permitted by mission operations and safety consideration, by removal of airbreathing engines, systems, and fuel from the orbiter. Structural limitations in the orbiter with design accelerations and factors of safety, could limit the maximum ascent cargo to about 65,000 lb. However, it may be possible to handle heavier payloads by limiting the maximum orbiter acceleration to something less than 3 g's and/or operating the vehicle with reduced factors of safety.

The data provided in Figure 4-16 includes abort to once-around capability; the method of achieving this is described as follows: if the total required mission delta velocity is equal to or greater than that indicated by Line B, then mission delta velocity is the driver. Sufficient propellants would be provided in the vehicle (because of mission requirements) to always accomplish the orbit to once-around. When the mission delta velocity is less than that of Line B, the abort to once-around capability is the driver and additional propellants must be included to accommodate the abort case. These additional propellants will be burned in the OMS and are derived from the ascent, attitude control, on-orbit maneuvering, and non-propulsive functions. Since the operating mixture ratio of the OMS engines is greater than that of the ACPS and the non-propulsive functions, an excess of approximately 3770 lb of oxygen is required when utilizing the non-propulsive propellants in the OMS during the abort mode.

When the shuttle is loaded for the abort case (abort delta V $>$ mission delta V) and a normal mission is flown, the total mission delta velocity available is indicated by Line A. This loading results in the maximum payload capability of the vehicle shown to the left of Line A. The break between Lines A and B represents burning of the excess O_2 for the mission delta velocity values between maximum payload (line A - abort capability the driver) and payload with abort (line B - mission delta velocity the driver).

Figure 4-17 presents the shuttle insertation payload capability as a function of orbit inclination. Shuttle performance as a function of mission delta velocity can be determined at inclinations other than the design and reference missions by cross plotting the data given in Figure 4-17.

Shuttle payload delivery capability to higher altitude orbits was derived for the above data and presented in Reference 4-1 for flight operations involving initial use of a 50 x 100 n mi insertion orbit, circularization in a 100 n mi circular parking orbit, and subsequent transfer to and circularization in the desired mission orbit. Improved shuttle payload capability for medium and high altitude missions can be achieved by employing a direct transfer orbit (rather than a 50 x 100 n mi injection orbit) to make full use of main tank propellant capacity. Figure 4-18 presents the estimated payload capability (orbiter ABES out) that could be achieved with the two stage, fully reusable shuttle through the use of a 50 n mi perigee direct insertion orbit. Low altitude performance is slightly different than that given in Figures 4-1 and 4-2 and is due to the higher abort allowance assumed for this direct injection mode.

The circular altitude orbit capability given in Figure 4-18 was attained utilizing direct reentry of the orbiter from the mission altitude. In every case, sufficient on-orbit delta velocity is provided in the shuttle to enable completion of a payload delivery mission and deboost and return of the orbiter, including intact abort capability, if required. This is achieved by fully loading the OMS tanks for every mission. The excess propellants in the OMS tanks that are not required for the on-orbit velocity increment of the particular mission is burned during the ascent phase, so that maximum payload capability is achieved.

Additional techniques for improving Space Shuttle payload capability (e.g., engine overspeed, propellant sharing, downrange landing, etc.) were investigated at various times by the contractors but were not included in the baseline Phase B shuttle designs. For this reason, these additional performance techniques are not covered in this report.

4.3.2 Two Stage Design With Orbiter External Tanks (OET)

Shuttle performance characteristics for a representative shuttle design in which the orbiter employs two external LH_2 tanks are given in Figures 4-19, 4-20, and 4-21. The performance characteristics were developed by Aerospace trajectory synthesis for the representative design (derived from a composite of contractor data). Pertinent system weight characteristics are listed below.

	Booster	Orbiter
Inert Weight	480,010*	265,118**
Payload	-	40,000***
Maneuver/ACS Propellant	830	17,485
Ascent Propellant	2,086,085	975,000
Inflight Losses	15,438	16,589
Gross Weight	2,582,363	1,314,192
Gross Liftoff Weight	3,896,555	

* Includes 51,678 lb of JP cruise fuel and 4,084 lb of reserve fluids

** Includes 17,306 lb of reserve fluids

*** Equivalent payload weight for south polar launch

Figure 4-19 presents the maximum insertion payload capability (orbiter ABES in) the OET shuttle can deliver to a 50 x 100 n mi orbit with parallel burn of the OMS during ascent. The three main engines employed in this design reduced the magnitude of the "worst case" engine-out abort penalty. Corresponding performance capability as a function of inclination is depicted in Figure 4-20.

As with the fully reusable shuttle, performance capability of the OET design to higher altitude orbits can be enhanced by use of a direct injection transfer orbit. Figure 4-21 presents the estimated maximum payload capability (orbiter ABES out) as a function of circular orbit altitude that could be achieved with the direct injection mode of operation.

4.4 REFERENCES

4-1. "Integrated Operations/Payloads/Fleet Analysis Final Report, Volume IV: Launch Systems, "Aerospace Corporation Report No. ATR-72(7231)-1 Volume IV, August 1971.

4-2. "Weight Reserves to Accommodate System Uncertainties," McDonnell Douglas Space Shuttle Program Technical Integration Design Note No. EAST-TI-15, 2 September 1970.

4-3. "Space Shuttle Monthly Mass Properties Status Report (MP-10)," McDonnell Douglas Phase B Systems Study Document No. DRL 04-09, 3 May 1971.

4-4. "Space Transportation System Fully Recoverable Two-Stage Earth Orbit Shuttle Weight Analysis," Aerospace Corporation Report No. TOR-0066(5759-02)-2, 15 May 1970

Table 4-1. Shuttle Weight Growth Projections for Cost Dispersion Estimate

- 10% Growth Allowance Required in Phase B Designs
- Projections Exclude Changes in System Requirements
- Projected Weights Not Indicative of Shuttle Design/Performance
  / Best Judgment Estimate for Costing

	BOOSTER			ORBITER		
	Baseline*	10% Growth+	Projected	Baseline*	10% Growth+	Projected
Aero Surfaces	66, 297	77, 862	77, 900	34, 051	37, 456	37, 500
Body/Tanks	192, 389	223, 537	238, 800	90, 884	99, 972	100, 000
Thermal Protection	76, 839	87, 881	91, 900	32, 196	35, 416	37, 000

* MDAC Mass Properties Report MP-9 Without Growth/Uncertainty Allowance

\+ Sized for 40, 000 Lb Payload (100 N Mi Polar Orbit) With 10% Weight Growth Allowance

Table 4-2. Space Shuttle Phase A/B Study Matrix

CONTRACTOR / CONFIGURATION	PHASE A STUDY			PHASE B STUDY	
	Grumman/ Boeing	LMSC	Chrysler	MDAC	NR
Single Stage to Orbit			X		
Stage and One-Half	X	X			
Two Stage Fully Reusable	X			X	X
Expendable Booster - Reusable Orbiter	X				
Drop Tank Orbiter - Reusable Booster/Orbiter	X			X*	X*
USAF Shuttle Impact Study				X	X

* Additional Study Effort for Three Months

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Table 4-3. NASA Phase A/B Vehicle Summary

SUBSYSTEM	UNIT	FAILURE RATE (λ), FAILURES PER HOUR, $A \times 10^{-B}$		NUMBER OF UNITS			
		A	B	3 YR MMD	4 YR MMD	5 YR MMD	WARNING
TELEMETRY, TRACKING, & COMMAND	L-S BAND ANT	9.00	8	1	1	1	1
	RCVR CONV CIU	6.34	6	2	2	2	3
	R-29	3.08	6	2	2	2	3
	PCM ENCODER	2.06	6	2	2	2	3
	XMTR CONV BASEBAND ASSY	9.34	7	1	1	2	2
	OMNI ANT	4.20	8	1	1	1	1
	S-BAND REPEAT ASSY	1.00	6	2	2	2	3
	S-BAND DIPLEXER	1.00	6	2	2	2	3
	S-BAND OMNI-DIPLEXER	1.00	6	2	2	2	3
	SOLID STATE SW	2.50	7	2	2	2	3
	COAXIAL SW	2.50	7	1	2	2	2
NAV	DATA FORMAT GEN	1.75	6	2	2	2	3
	QUAD MOD + PA DRIVER	2.63	6	2	2	2	3
	BIPHASE MOD + PA DRIVER	5.16	6	1	2	2	2
	OSC	8.77	6	4	4	5	5
	FREQ SYN	2.29	6	2	2	2	3
	TWTA AJ	1.04	5	2	2	2	3
	TWTA CLEAR	1.04	5	2	2	2	3
	TLM BUFFER	1.00	6	2	2	2	3
	TIME BASE GEN	3.00	6	2	2	3	3
	STORAGE + ELECTRONICS	4.27	6	2	2	3	3
	PN GEN	1.25	5	3	3	3	3

Table 4-3. NASA Phase A/B Vehicle Summary (Cont'd)

CHARACTERISTIC	CONFIGURATION	TWO STAGE-EXTERNAL DROP TANK ORBITER						STAGE & ONE-HALF
	CONTRACTOR	MDAC		NR		G/B		LMSC [1]
	GLOW	4,123,819		3,896,070		3,925,260		3,816,420
	Element	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Orbiter
WEIGHT (Lb.)	GLOW	2,080,093	2,043,726	2,724,840	1,171,230	2,824,000	1,101,260	630,486
	Dry [2]	345,856	238,663	439,867	218,124	494,870	197,238	294,399
	Structure Factor	0.207	0.160 [3]	0.189	0.234 [3]	0.205	0.224 [3]	0.539 [2]
	External Tank - Inert (Ea.)	-	23,133	-	10,085	-	11,800	30,679
DIMENSIONS	Length (Ft.)	218.0	175.0	222.3	181.7	245.0	157.0	156.5
	Span (Ft.)	117.0	115.0	122.2	109.4	177.5	97	92
	Height (Ft.)	55.0 [4]	64.4 [4]	85 [5]	61 [5]	88.3 [5]	75.5 [5]	49 [5]
	Total Wetted Area - $Ft.^2$	26,660	22,808	NA	NA	33,794	17,930	18,944
	Body Encl. Vol. - Ft^3	117,030	79,618	147,191	74,296	178,440	58,400	97,600
PROPULSION	Main Eng No/Thrust Ea.	7/550K (SL)	3/632K (Vac.)	13/415K (SL)	3/477K (Vac.)	12/415K (SL)	3/477K (Vac.)	9/530K (SL)
	OMS No/Type	-	2/RL-10	-	3 @ 10K	-	2/RL-10	2/RL-10
	ACPS-No.	16	28	26	29	34	30	32
	ABES Type/No.	F101/F12B-3/8	F101/F12B-3/4	JTF22A-4/8	JTF22A-4/4	F101/F12B-3/8	JTF-22A4/4	JTF-22B/6
B/O RELATIVE STAGING VELOCITY (FPS)		6,190		7,333		7,000		18,000
REF. FIGURE		4-11		4-12		4-13		4-14

(1) Sized by 25K Payload with ABES, 55° Mission
(2) Excludes Drop Tanks
(3) Includes Drop Tanks
(4) From Bottom of Fuselage to Top of Vertical Stabilizer
(5) From Static Ground Line to Top of Vertical Stabilizer

Table 4-4. Summary Weight Comparison - Phase B Space Shuttle Final Designs

	2 STAGE FULLY REUSABLE						EXTERNAL H_2 TANK					
	North American		McDonnell		Grumman		North American		McDonnell		Grumman	
	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter
Structure												
Aerosurfaces	76,971	26,953	77,168	36,360	155,282	26,577	60,064	29,989	54,588	40,457	93,000	25,347
Body/Tank Structure	228,531	84,920	187,494	78,990	264,225	86,186	144,751	68,811	130,280	78,548	225,170	69,529
Landing Gear	28,457	16,504	25,885	10,551	49,962	11,941	19,163	16,137	21,248	10,784	22,700	10,313
Thermal Protection System	86,024	38,588	84,807	28,936	105,909	43,495	35,716	37,889	10,207	31,572	4,700	36,722
Avionics	5,582	3,790	4,941	4,588	2,800	3,385	4,633	3,790	4,941	4,588	2,800	3,395
Power Supply and Distribution							47,524*	15,831				
Electrical	3,612	6,040	5,400	3,575	4,527	3,608	--	--	4,901	3,575	2,520	3,456
Hydraulic	11,821	3,186	18,602	8,004	17,103	5,369	--	--	12,944	8,004	13,360	5,305
Environmental Control	3,284	4,613	2,346	8,106	600	2 422	2,935	4,613	1,448	7,949	600	2,422
Rocket Engines												
Primary	101,401	19,222	98,241	19,422	105,747	19,072	68,575	18,810	57,486	29,423	70,080	20,408
Secondary	--	803	--	917	--	700	--	803	--	917	--	700
Airbreathing Engines	29,330	544	28,084	574	29,500	1,219	23,239	0	22,493	574	23,840	1,129
Attitude Control Thrusters	1,215	1,174	549	1,291	1,500	1,120	1,200	1,500	549	1,291	1,480	1,120
Contingency	50,705	17,094	42,483	20,552	61,293	15,041	32,063	19,953	24,771	20,981	34,620	17,392
External Tanks							--	20,172	--	46,266	--	23,600
DRY WEIGHT	626,933	223,431	576,000	221,866	798,448	220,135	439,868	238,296	345,856	284,929	494,870	220,838
Personnel	476	618	522	626	600	458	476	618	522	626	400	458
Payload	--	40,000	--	40,000	--	40,000	--	40,000	--	40,000	--	40,000
Propellants, Fluids & Residuals	3,560,814	595,055	3,179,031	590,916	3,503,592	677,687	2,284,496	892,315	1,733,715	1,718,171	2,328,730	839,964
GROSS WEIGHT	4,188,223	859,104	3,755,553	853,408	4,302,640	938,280	2,724,840	1,171,230	2,080,093	2,043,726	2,824,000	1,101,260
GROSS LIFTOFF WEIGHT	5,047,327		4,608,961		5,240,920		3,896,070		4,123,819		3,925,260	

*Includes 22,700 lb for separation.

Table 4-5. Space Shuttle - Phase B Extension Studies, Reusable Orbiter

(1) (4) Configuration	H. O.	H. O.	H. O.	H	H
Payload Size	15 x 60 Ft.	15 x 40 Ft.	12 x 40 Ft.	15 x 60 Ft.	12 x 40 Ft.
260" Solid	MDAC/MMC (3) NAR/GDC GAC/BAC LAC	MDAC/MMC NAR/GDC GAC/BAC LAC	MDAC/MMC NAR/GDC GAC/BAC LAC	MDAC/MMC NAR/GDC LAC	
Clustered 120" - 156" Solids	MDAC/MMC NAR/GDC GAC/BAC LAC			GAC/BAC	MDAC/MMC GAC/BAC
Titan IIIL	MDAC/MMC		MDAC/MMC	MDAC/MMC	
Saturn S-IC	GAC/BAC			GAC/BAC	
Interim (2) Core	NAR/GDC		NAR/GDC	NAR/GDC	

1. Configuration H. O. - Hydrogen and oxygen external tanks (all propellants external)
   H - Hydrogen external tanks only
2. Interim Core - Propellant tanks and structure sized to final recoverable booster configuration
3. Baseline Case for All Contractors
4. All Configurations of Orbiter and Booster to be Sized to Eventually be Used with Heat Sink Type Recoverable Booster.

Table 4-6. Space Shuttle Subsystem Technology Assumptions

SUBSYSTEM	MARK I ORBITER	MARK II ORBITER	REUSABLE BOOSTER
Structures	External HO Tanks	No Change	LO_2/RP(F-1)
Body	Max. Aluminum	No Change	Max. Aluminum
Aerosurface	Max. Aluminum	No Change	Max. Aluminum
External Tanks	Max. Aluminum	No Change	None
TPS	Ablator SLA 561 (Martin) ESA 3560 (Martin)	RSI	Heat Sink (SLA 561 where required)
Propulsion			
RCS	Hypergolic	No Change	Hypergolic
OMS	LM Ascent (2)	No Change	None
Main	J-2 (4)	High P_c (4)	F-1 (Reus. Modif)
ABES	GE F101/F12A3 (2)	No Change	GE F101/F12A3 (12)
Avionics	Current Airplane & Spacecraft Avionics	Limited Product Improvement	Current A/C and S/C
Power			
EPS	Fuel Cells (3)	No Change	747/SST
APU's	Mono Prop. (N_2H_4)	No Change	Hypergolic
Hydraulic	3000 psi	No Change	3000 psi
ECLSS	Current A/C & S/C	No Change	Current A/C & S/C

Table 4-7. Space Shuttle Study Extension Effort Focus for Next Seven Weeks

Study Contractor Effort 7-Week Period	McDonnell/ Martin	NR/GDC	Grumman/ Boeing	LMSC
ORBITER				
HO Mark I - Mark II	X	X	X	X
RATO/TAHO	10%		10%	
1-1/2 Stage				10%
REUSABLE BOOSTER				
F-1/LOX-RP	X	X	X	
Ballistic System	X	X	X	
INTERIM BOOSTER				
Titan III L	STOP			
S-1C			X	
Solids	STOP	STOP	STOP	X (156")

NOTES:
- X — Major Effort
- STOP — Phase-Out Work and Submit Report
- 10% — Maximum Percentage of Funded Effort

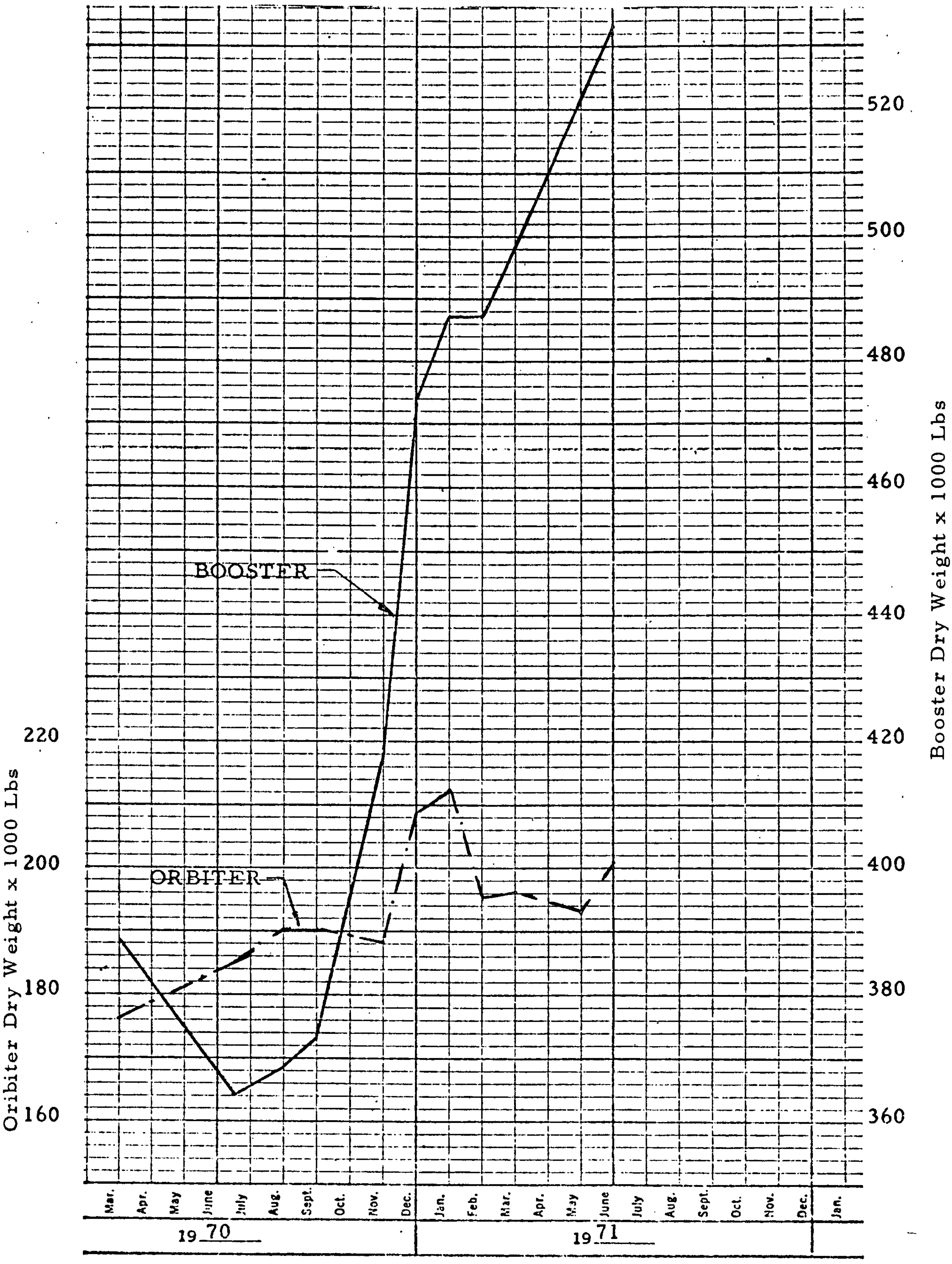


Figure 4-1. MDAC Space Shuttle Booster and Orbiter Dry Weight Variations (Less Growth Allowance)

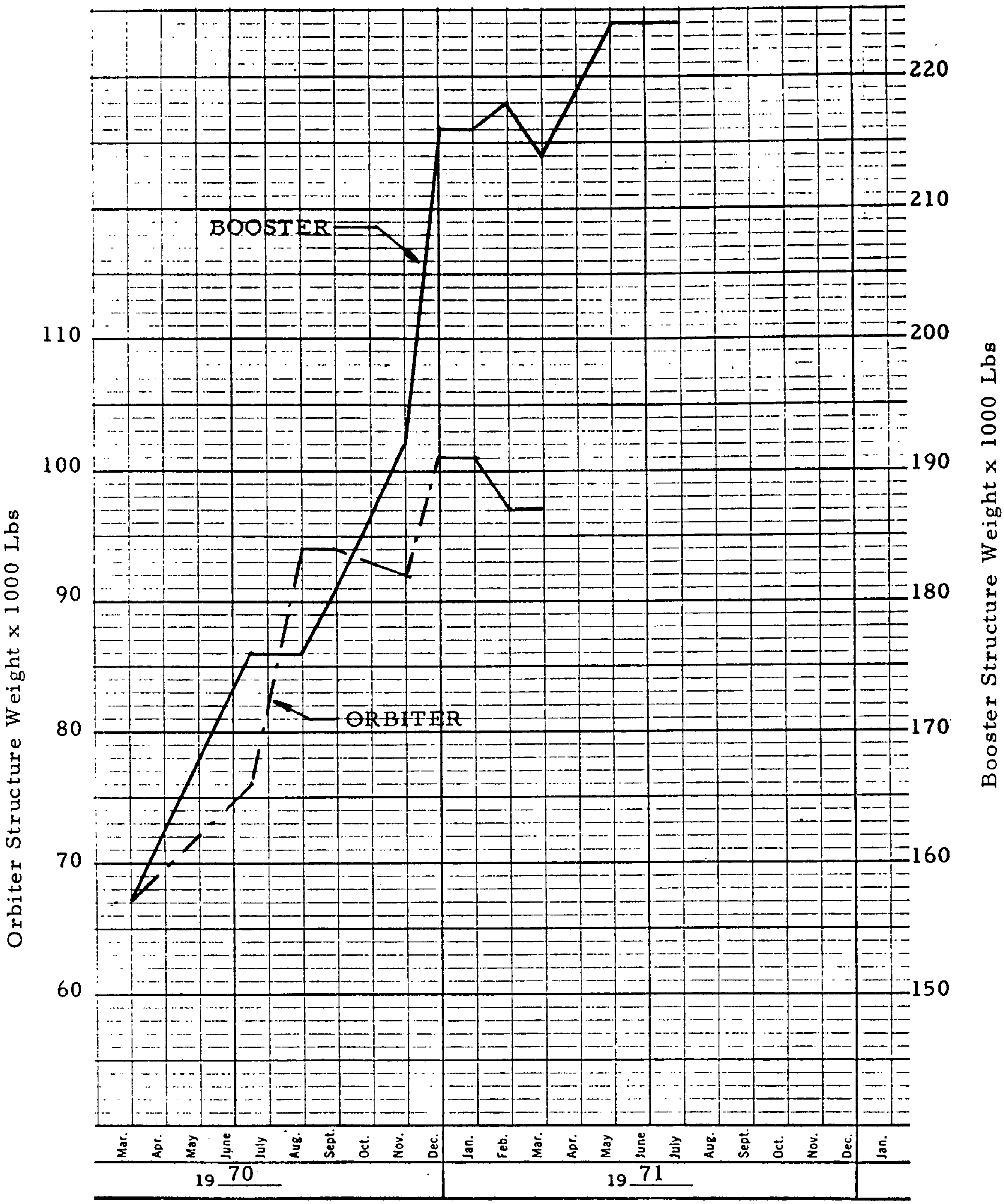


Figure 4-2. MDAC Space Shuttle Booster and Orbiter Structure Weight Variations

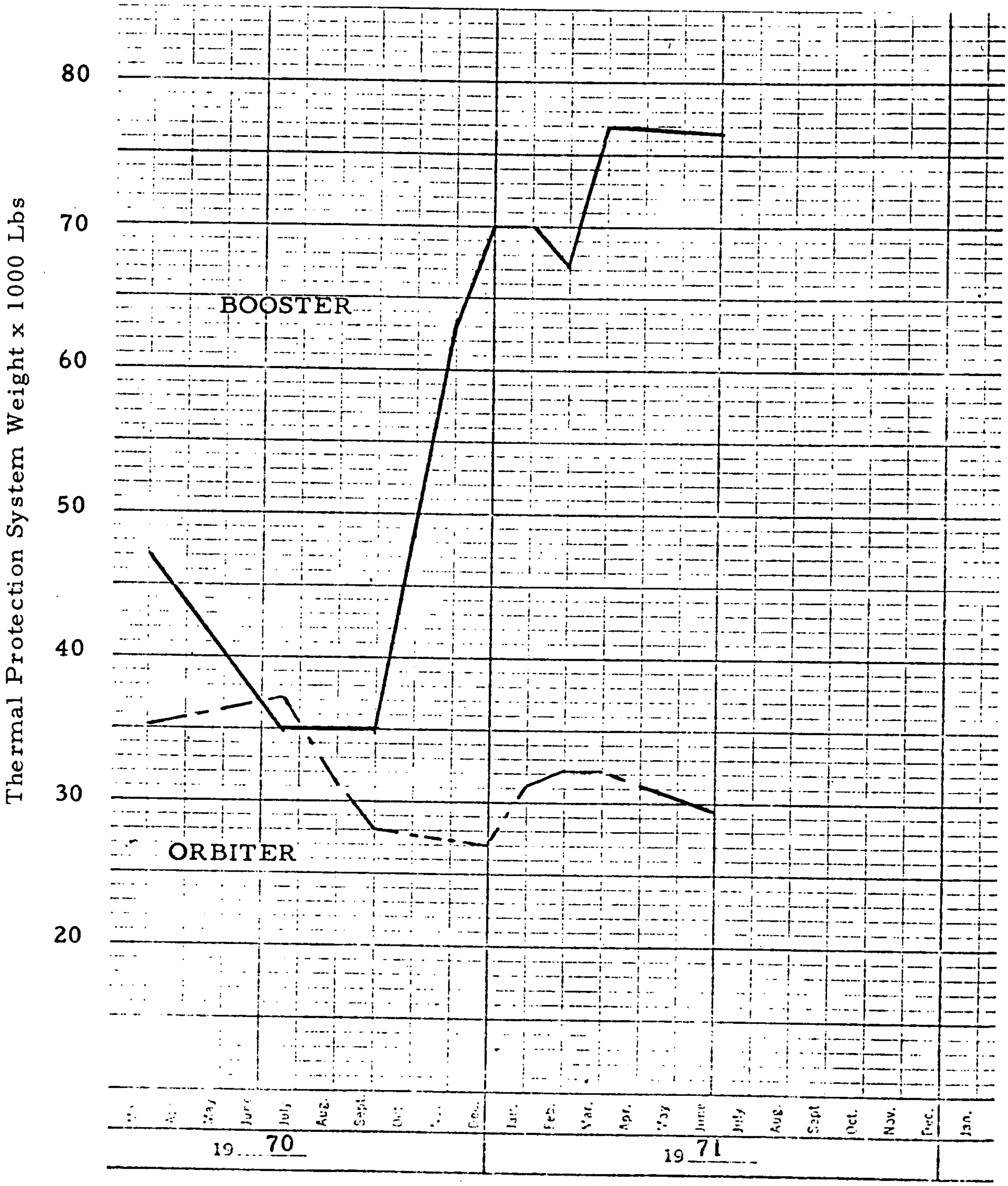


Figure 4-3. MDAC Space Shuttle Thermal Protection System Weight, Booster and Orbiter

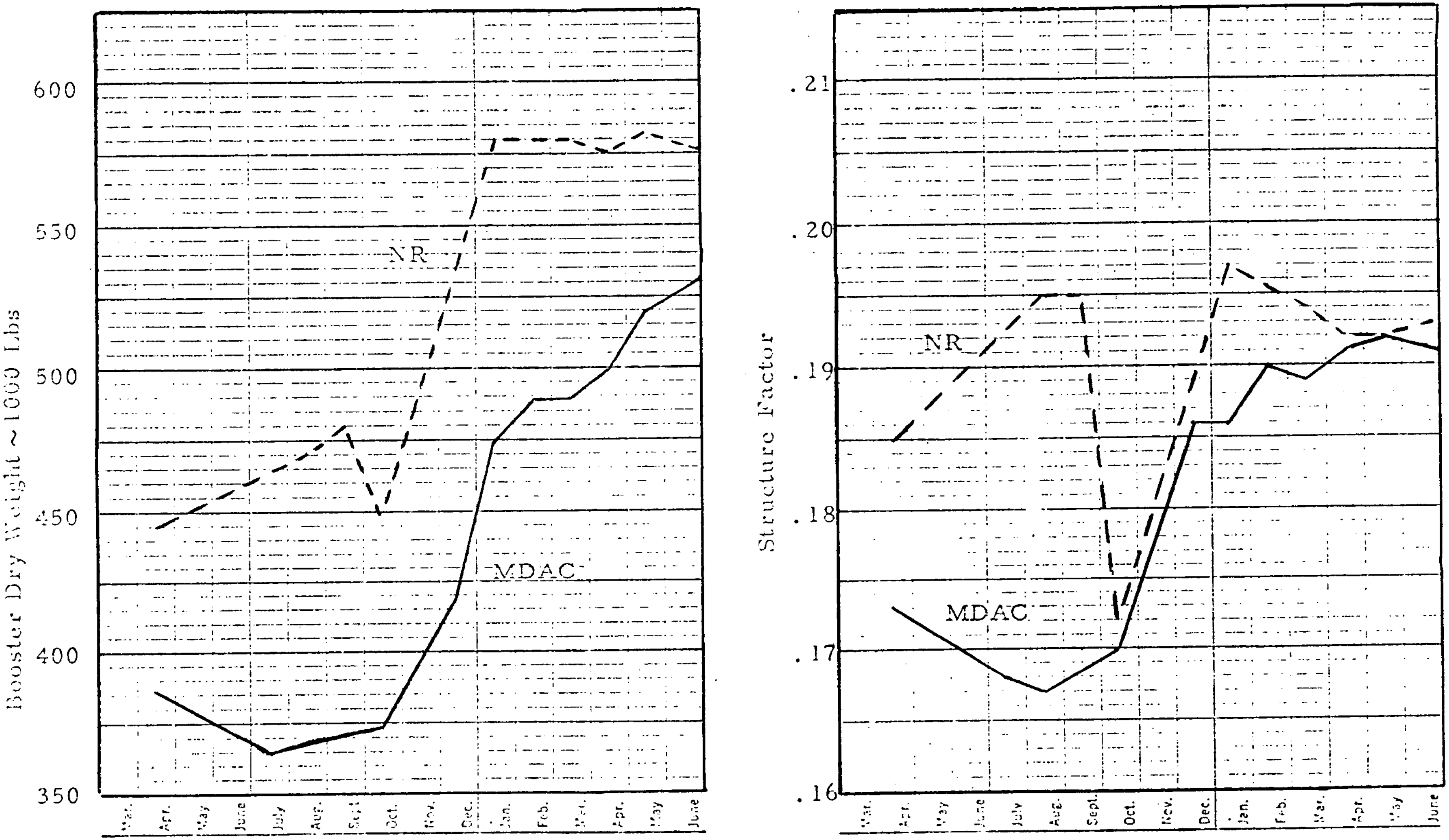
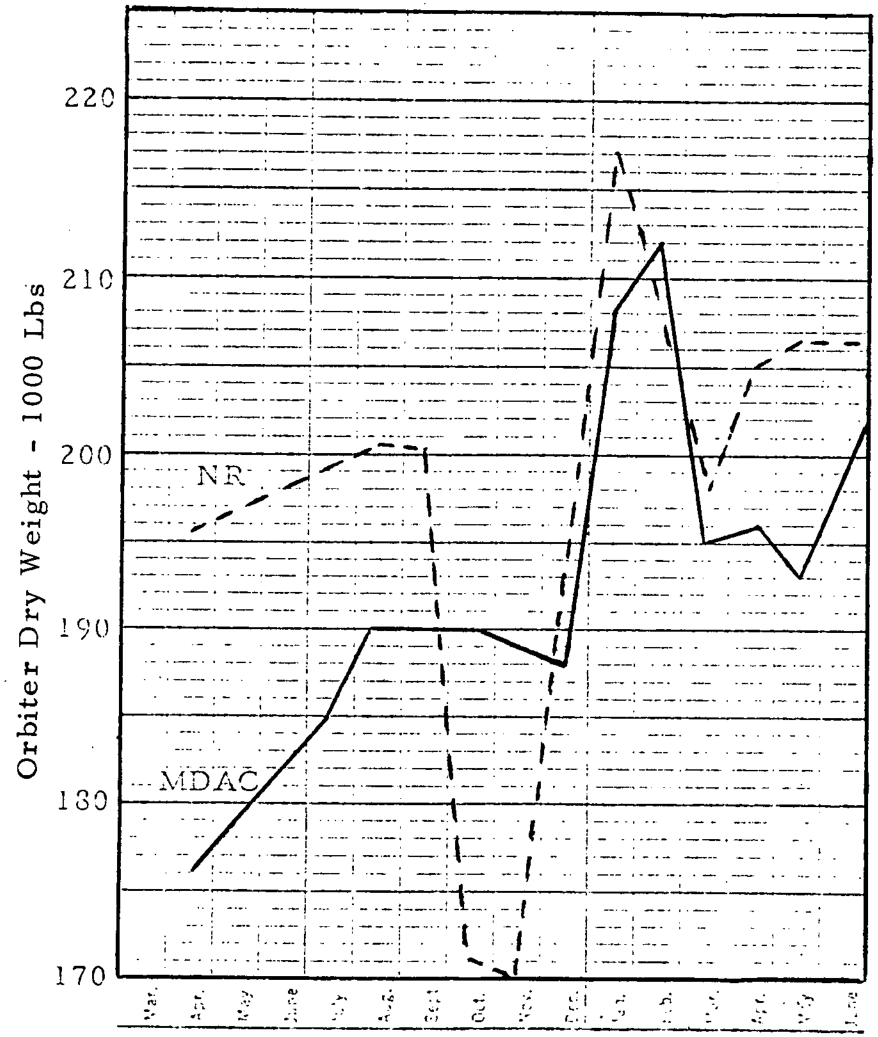


Figure 4-4. Phase B Booster Dry Weight (Less Growth Allowance) And Structure Factor Trends



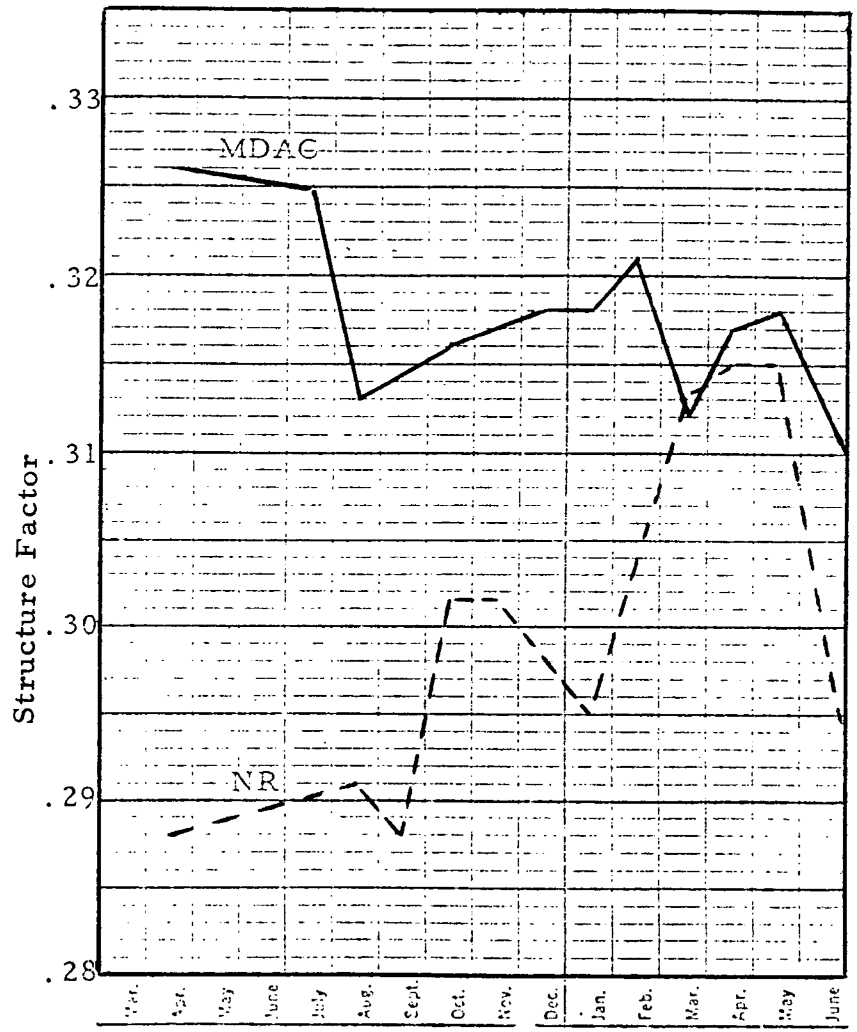


Figure 4-5. Phase B Orbiter Dry Weight (Less Growth Allowance) And Structure Factor Trends

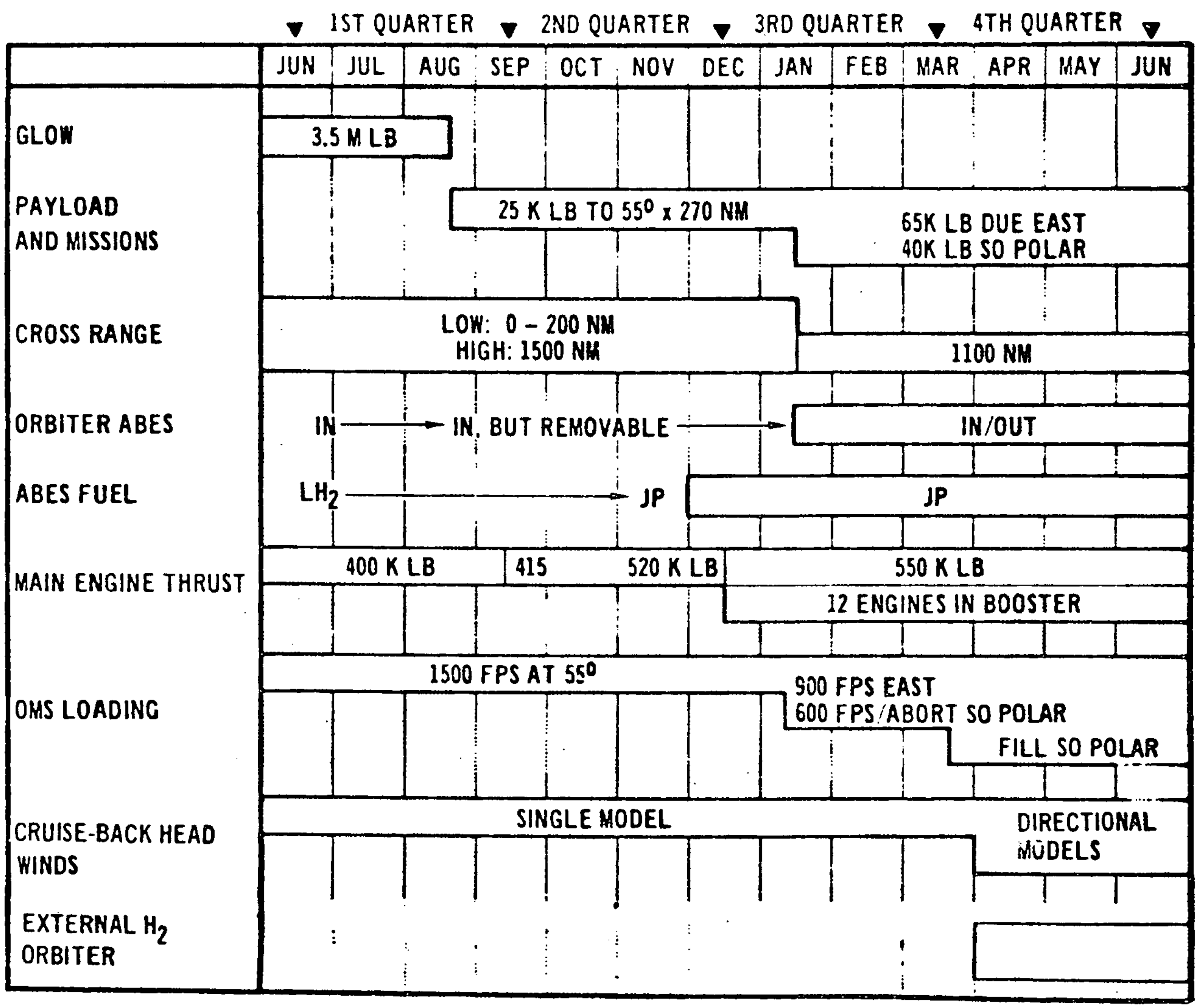
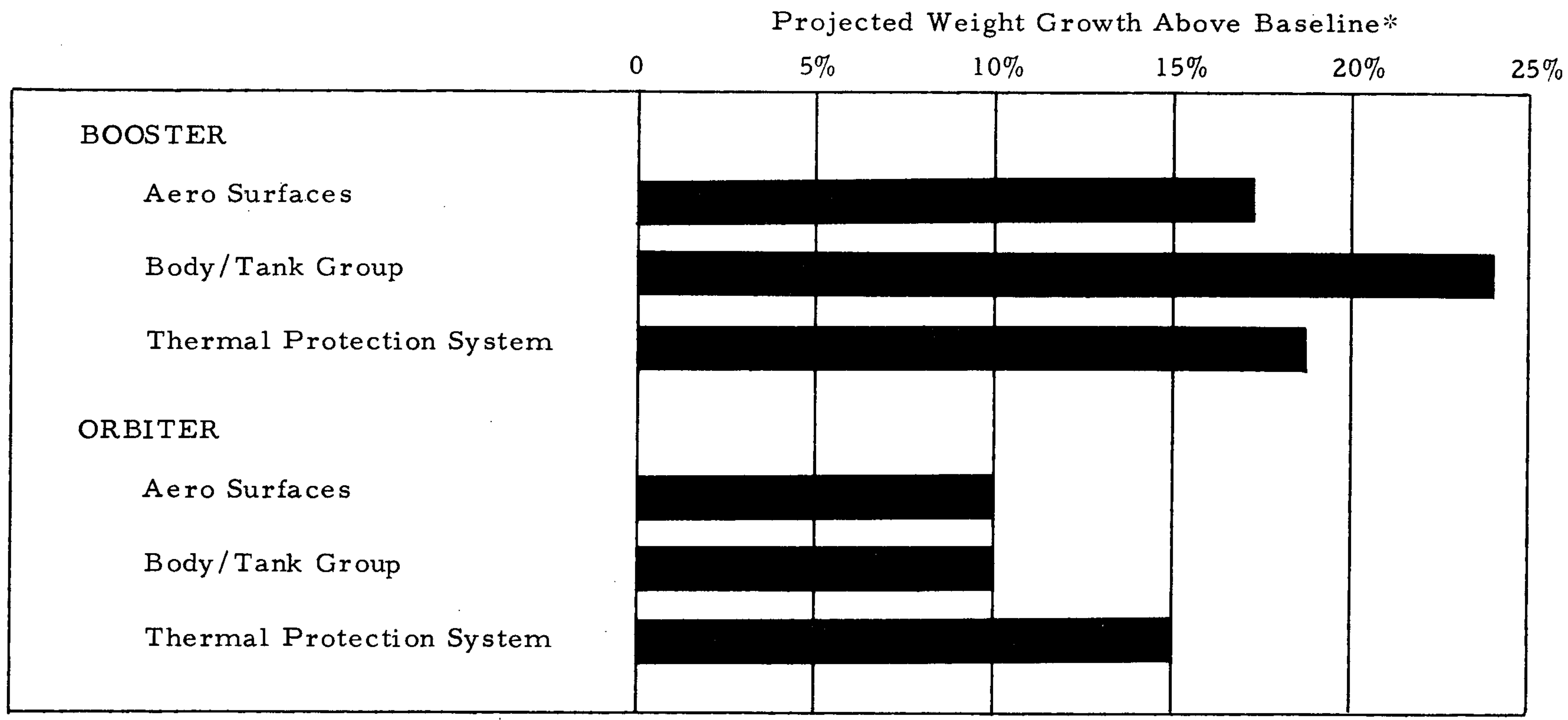


Figure 4-6. Space Shuttle Program
Major Requirements Evolution During FY 1971



* MDAC Mass Properties Report MP-9

Figure 4-7. Space Shuttle Weight Growth Projections For Cost Dispersion Estimate

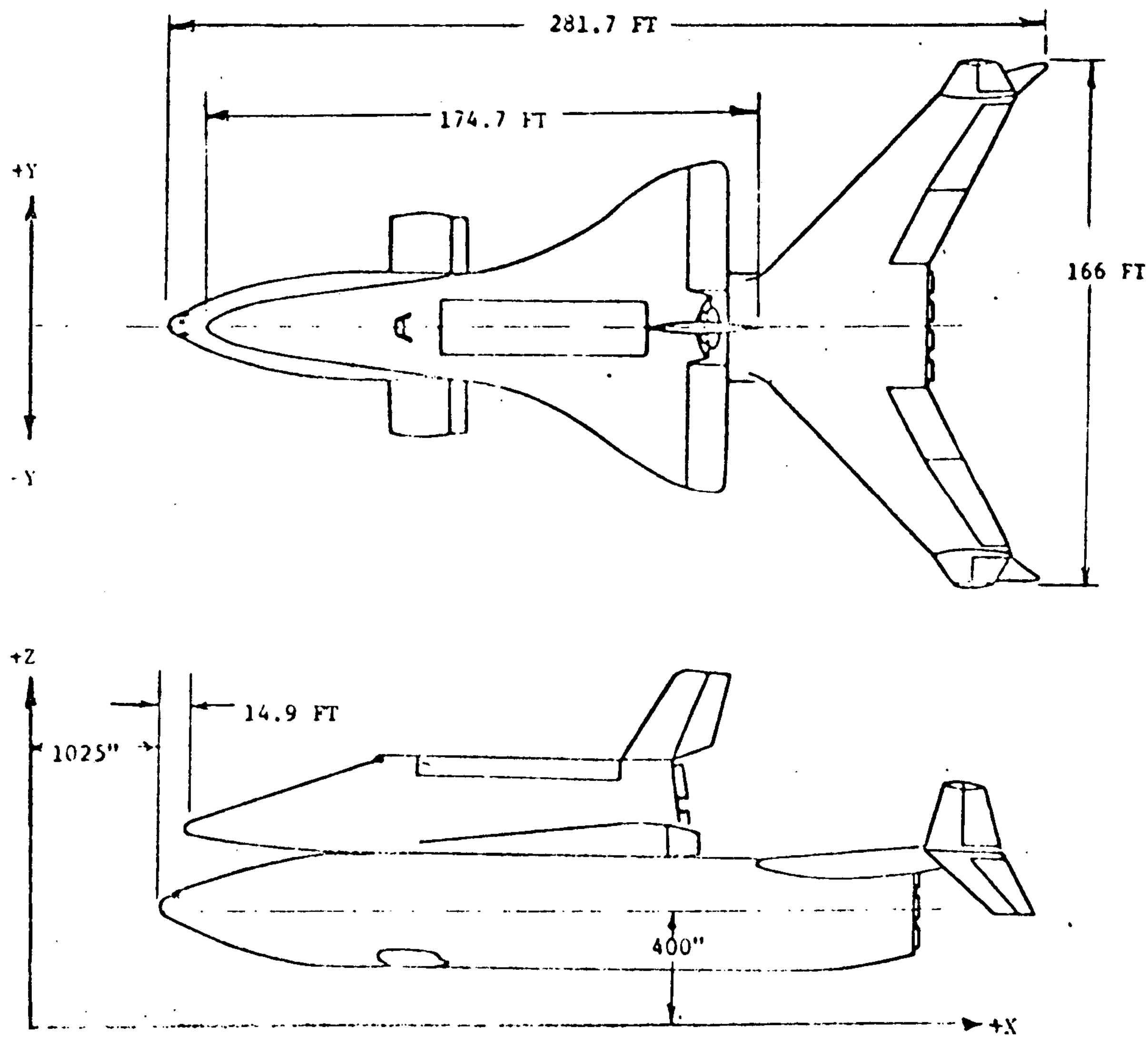


Figure 4-8. MDAC Two-Stage Fully Reusable Space Shuttle Configuration

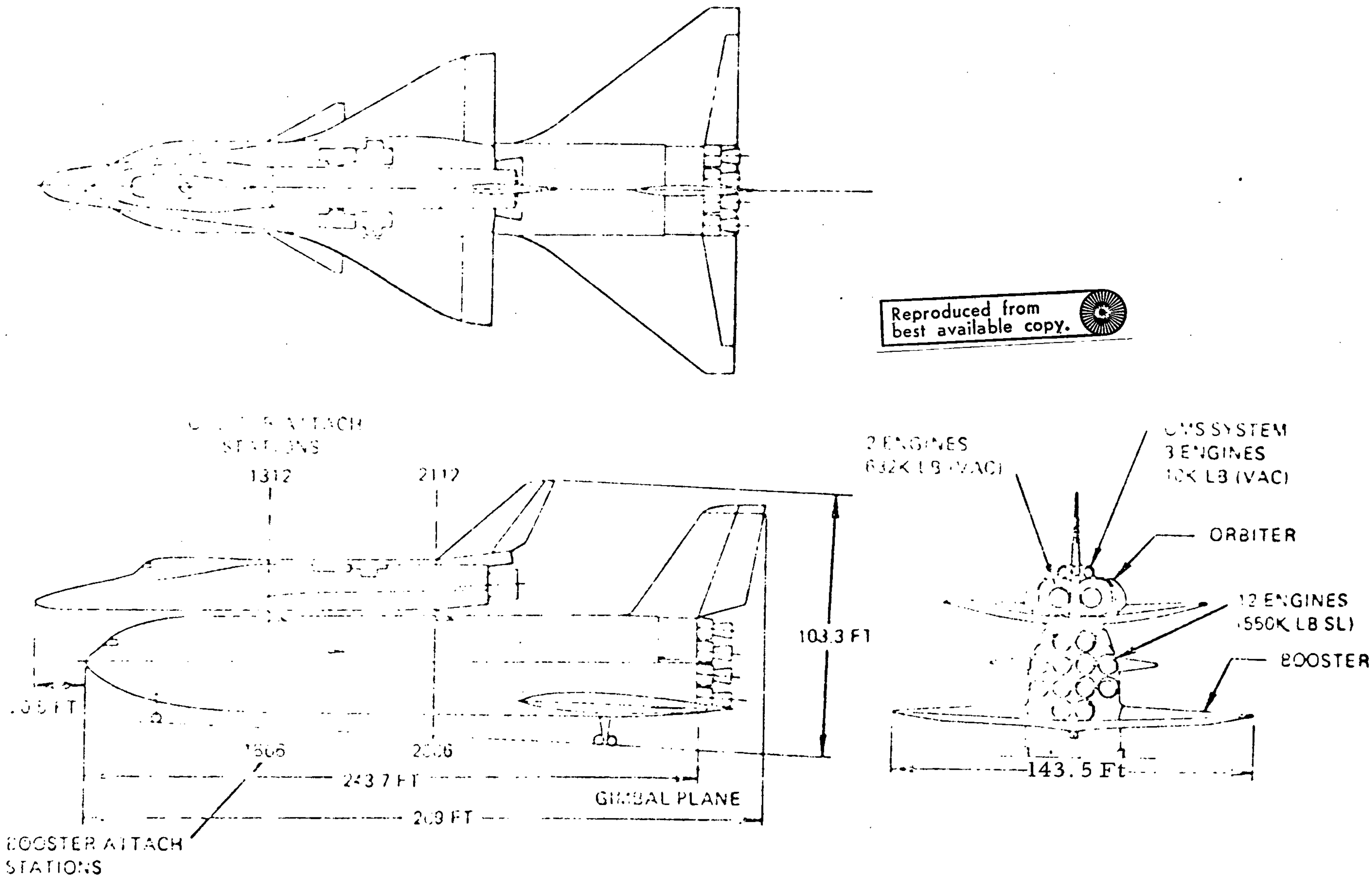


Figure 4-9. NR Two-Stage Fully Reusable Space Shuttle Configuration

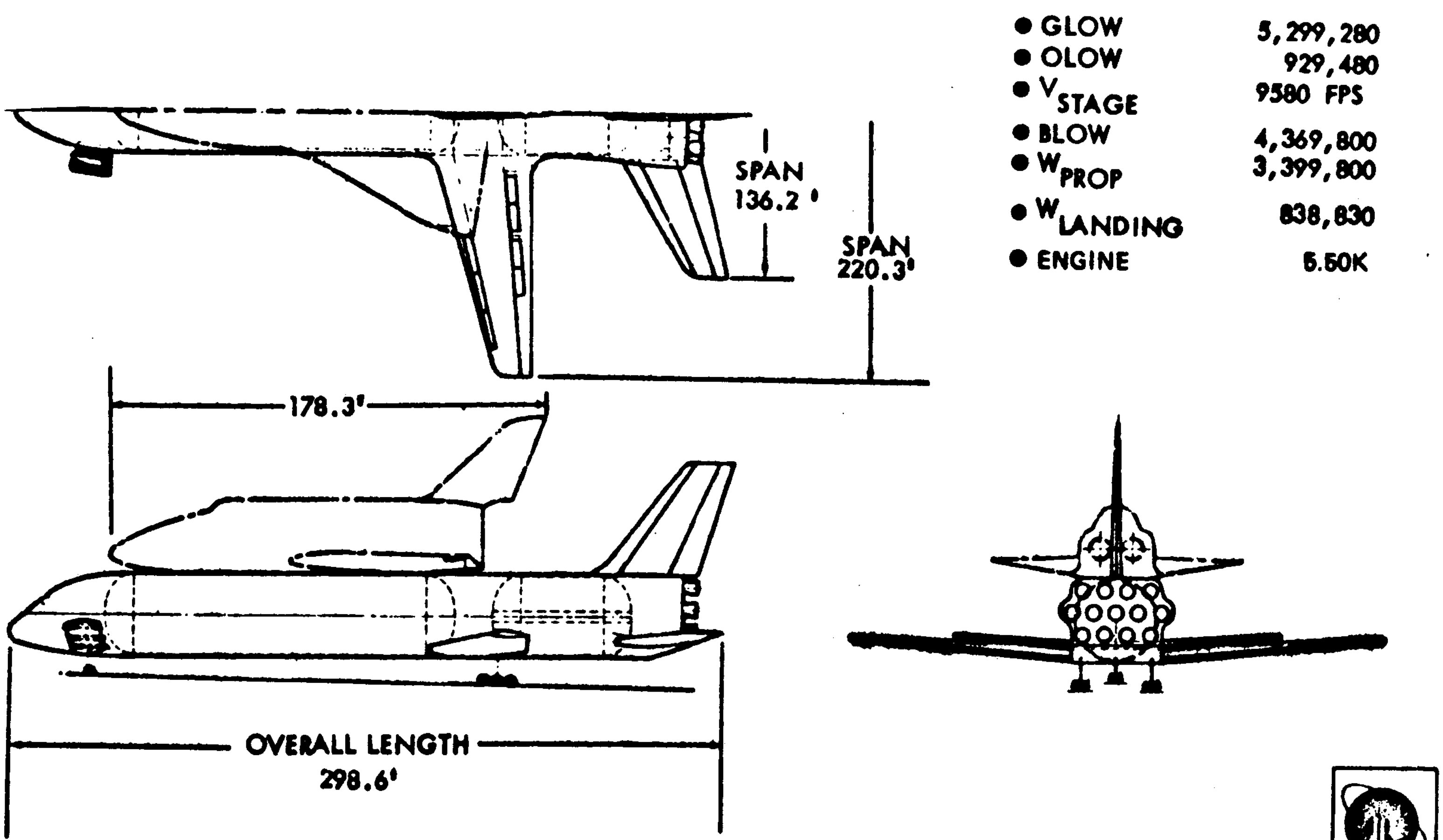


Figure 4-10. GAC/BAC Two-Stage Fully Reusable Space Shuttle Configuration

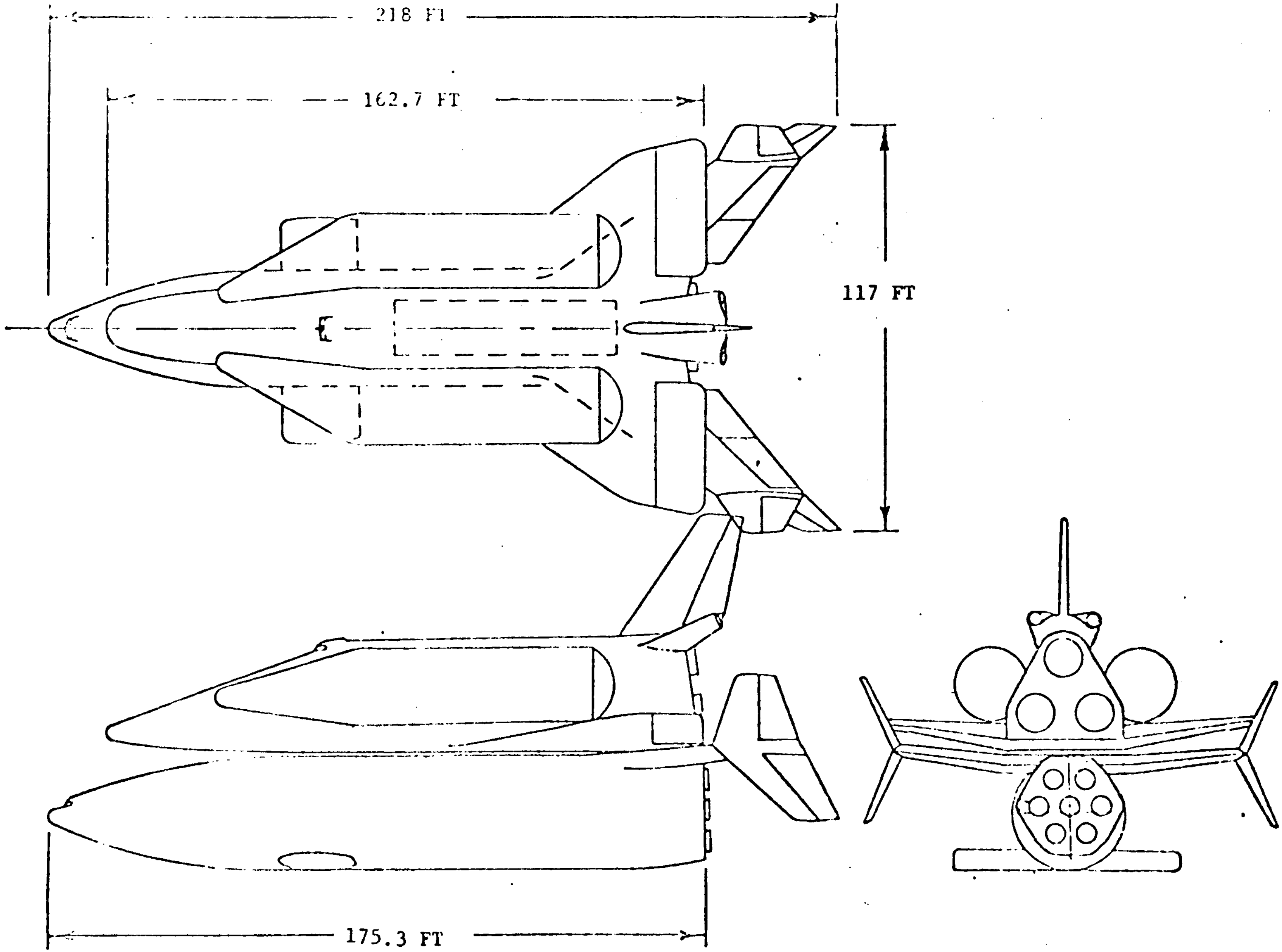


Figure 4-11. MDAC External LH_2 Drop Tank Space Shuttle Configuration

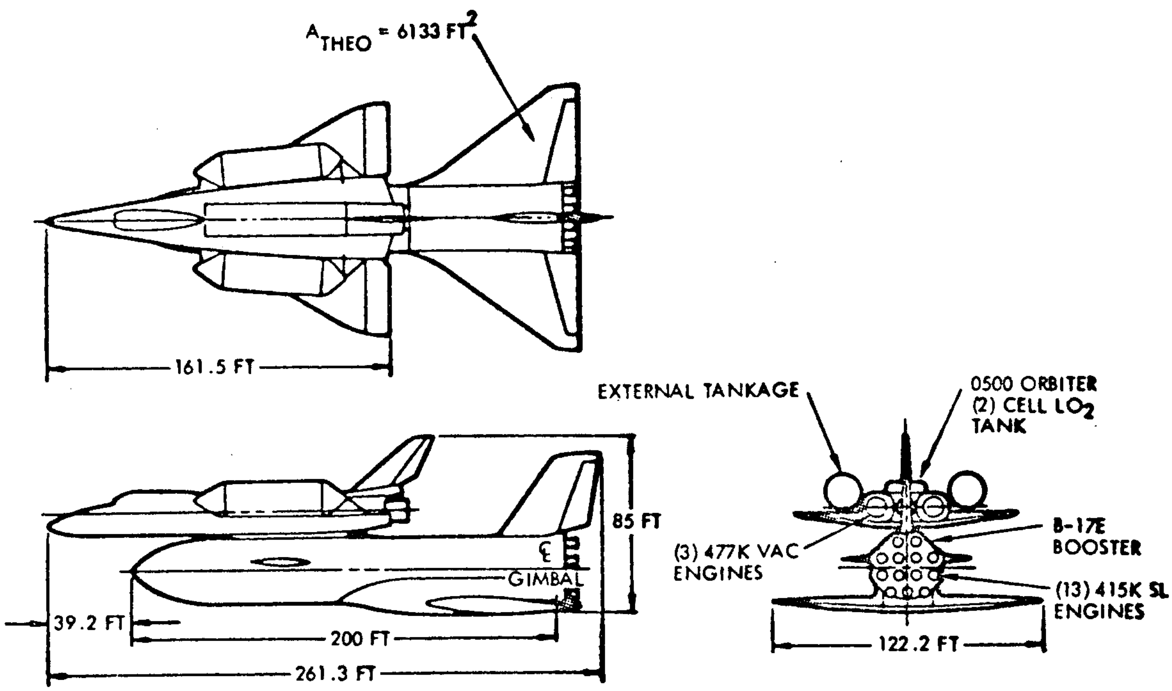


Figure 4-12. NR External LH_2 Drop Tank Space Shuttle Configuration

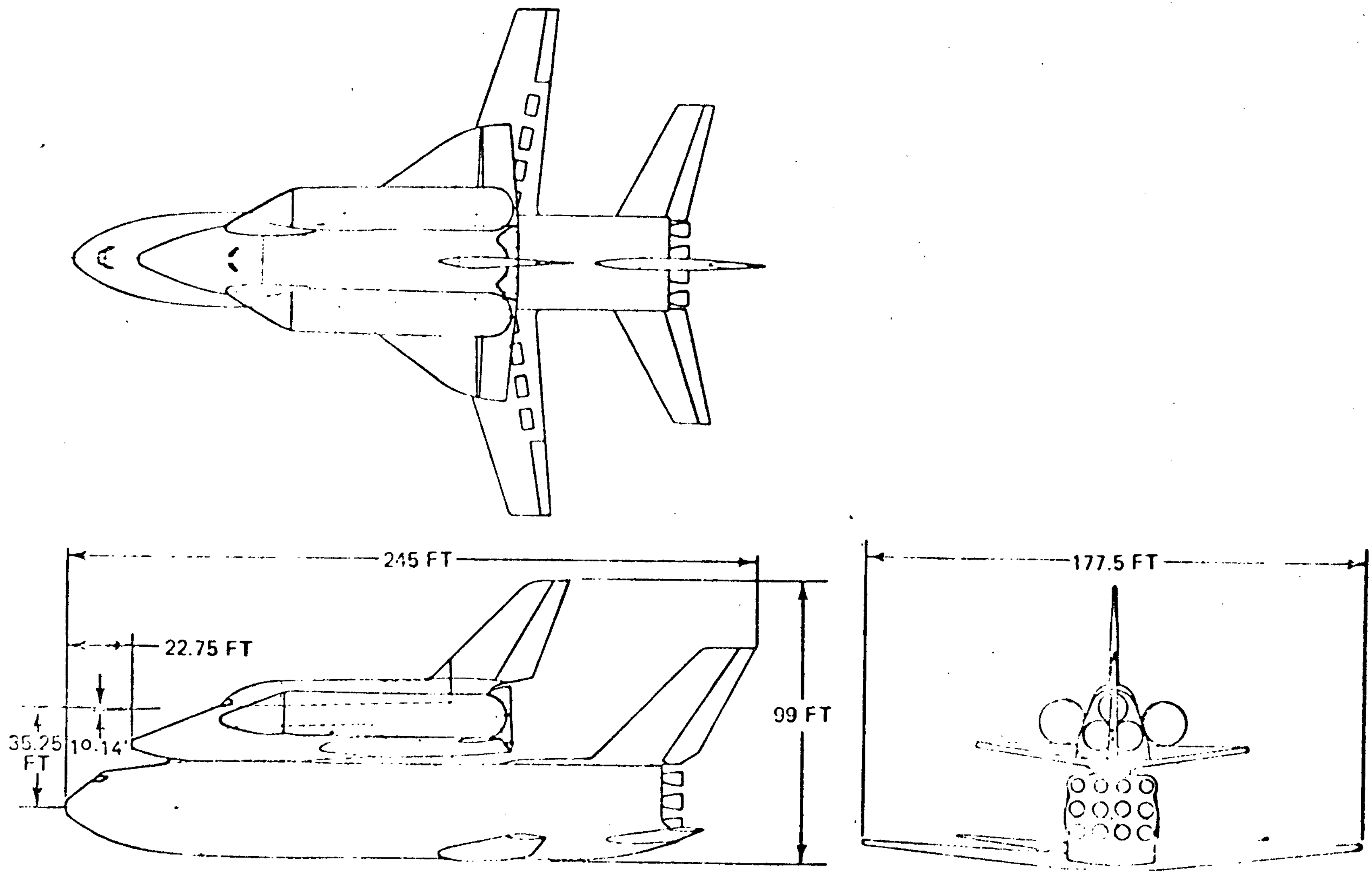


Figure 4-13. GAC/BAC External LH_2 Drop Tank Space Shuttle Configuration

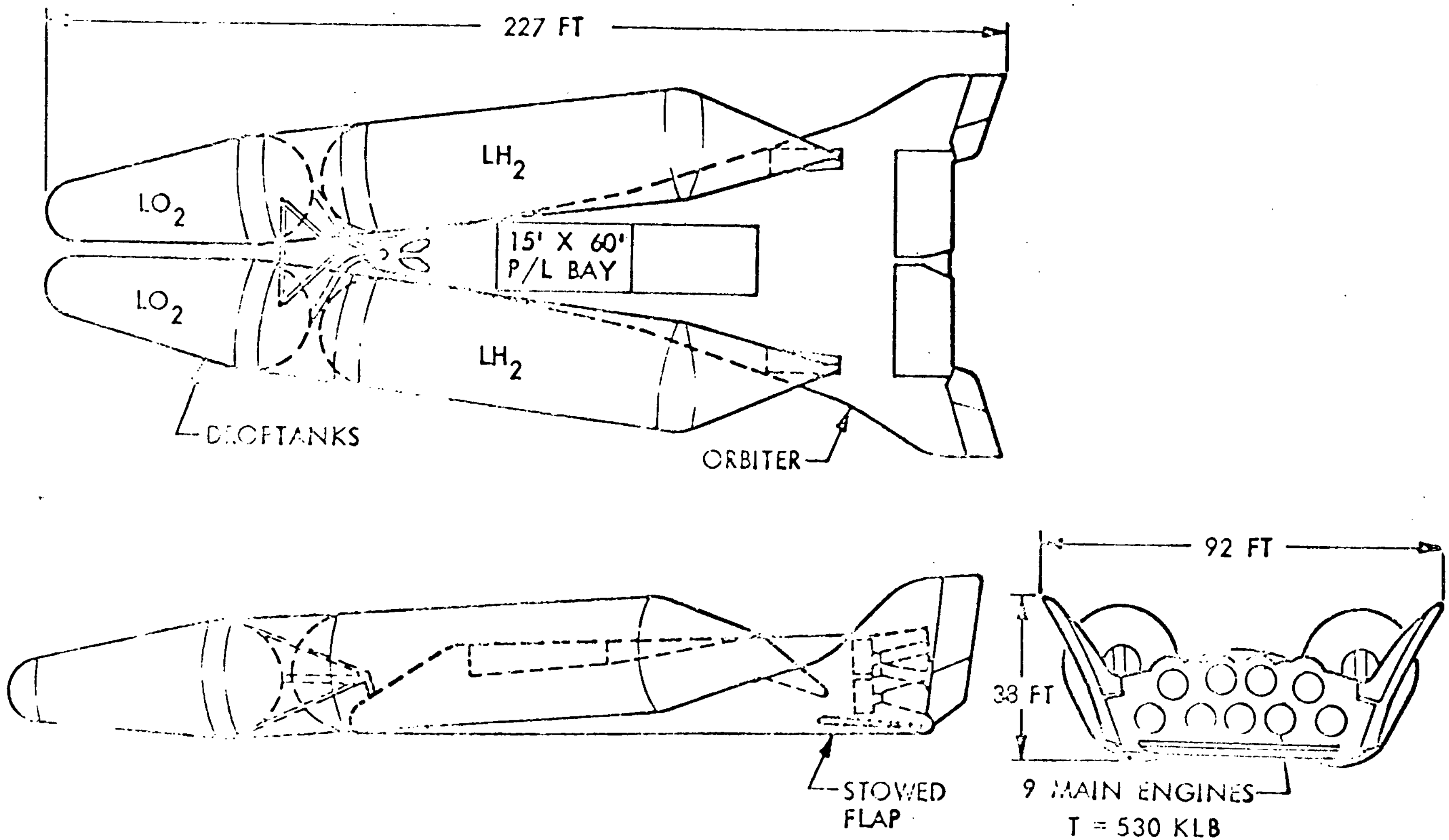


Figure 4-14. LMSC Stage And One-Half Shuttle Configuration

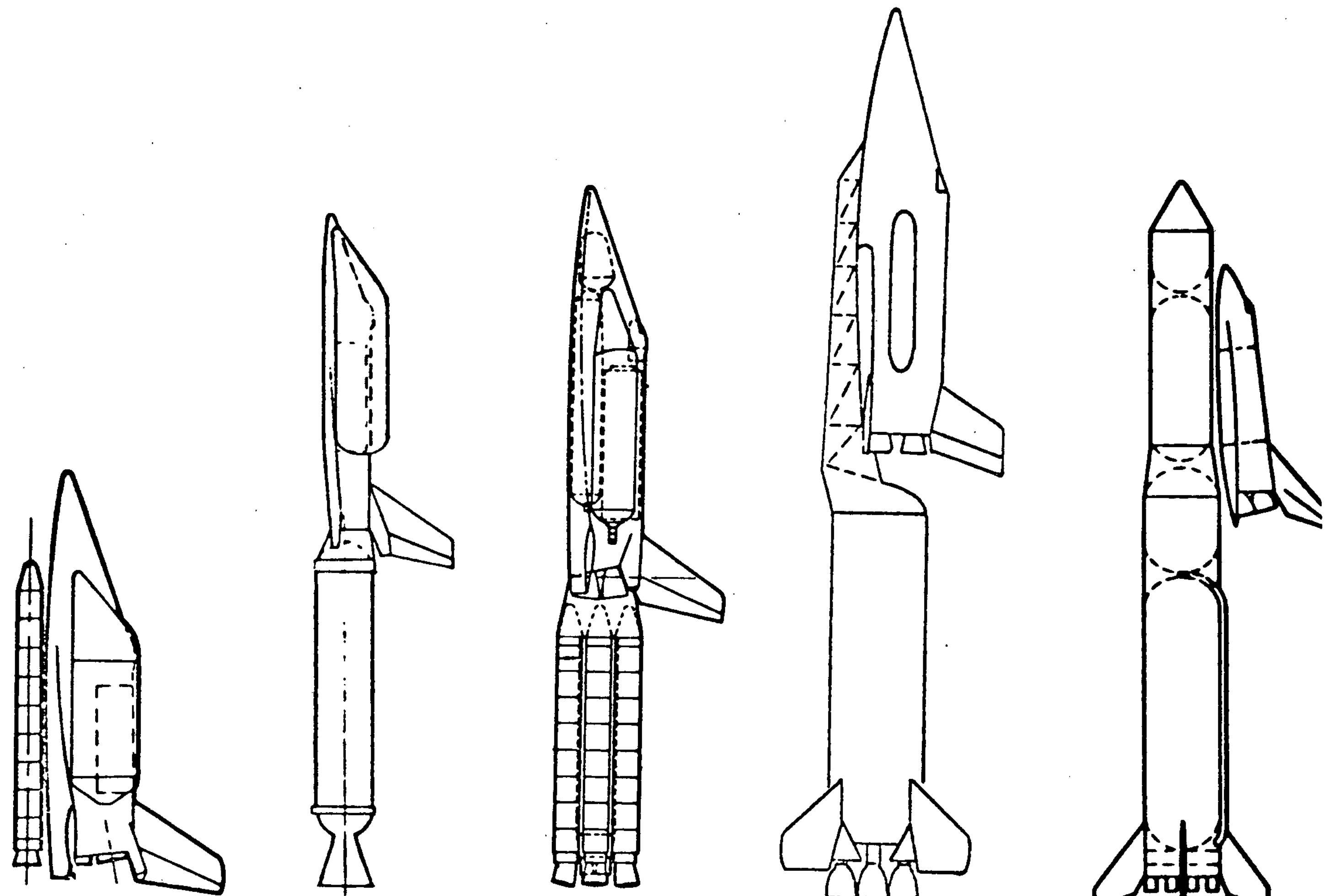


Figure 4-15. Space Shuttle Phase B Extension Study Configurations

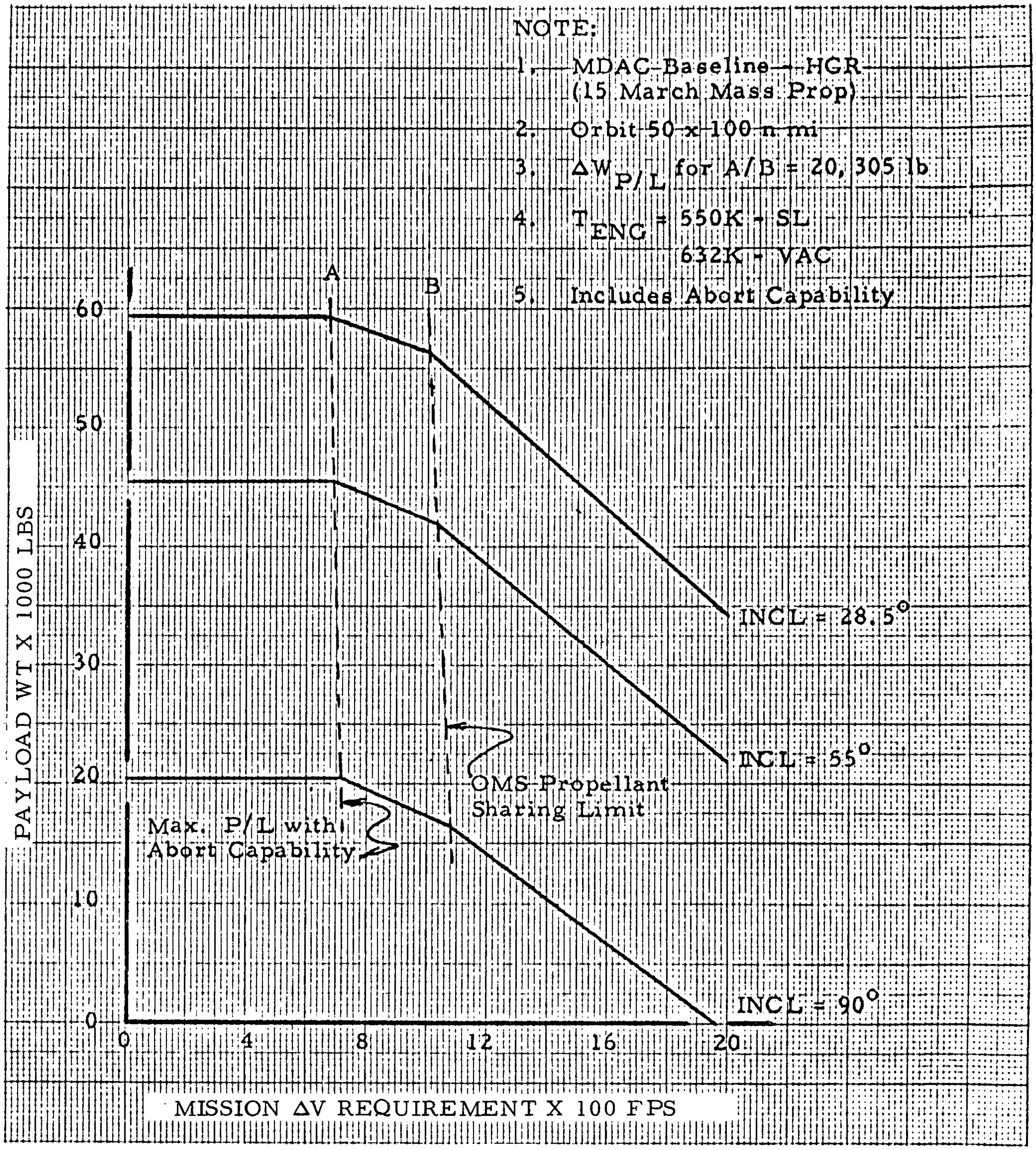


Figure 4-16. Space Shuttle Performance Capability
Payload Versus Mission Velocity, Two-Stage Fully Reusable

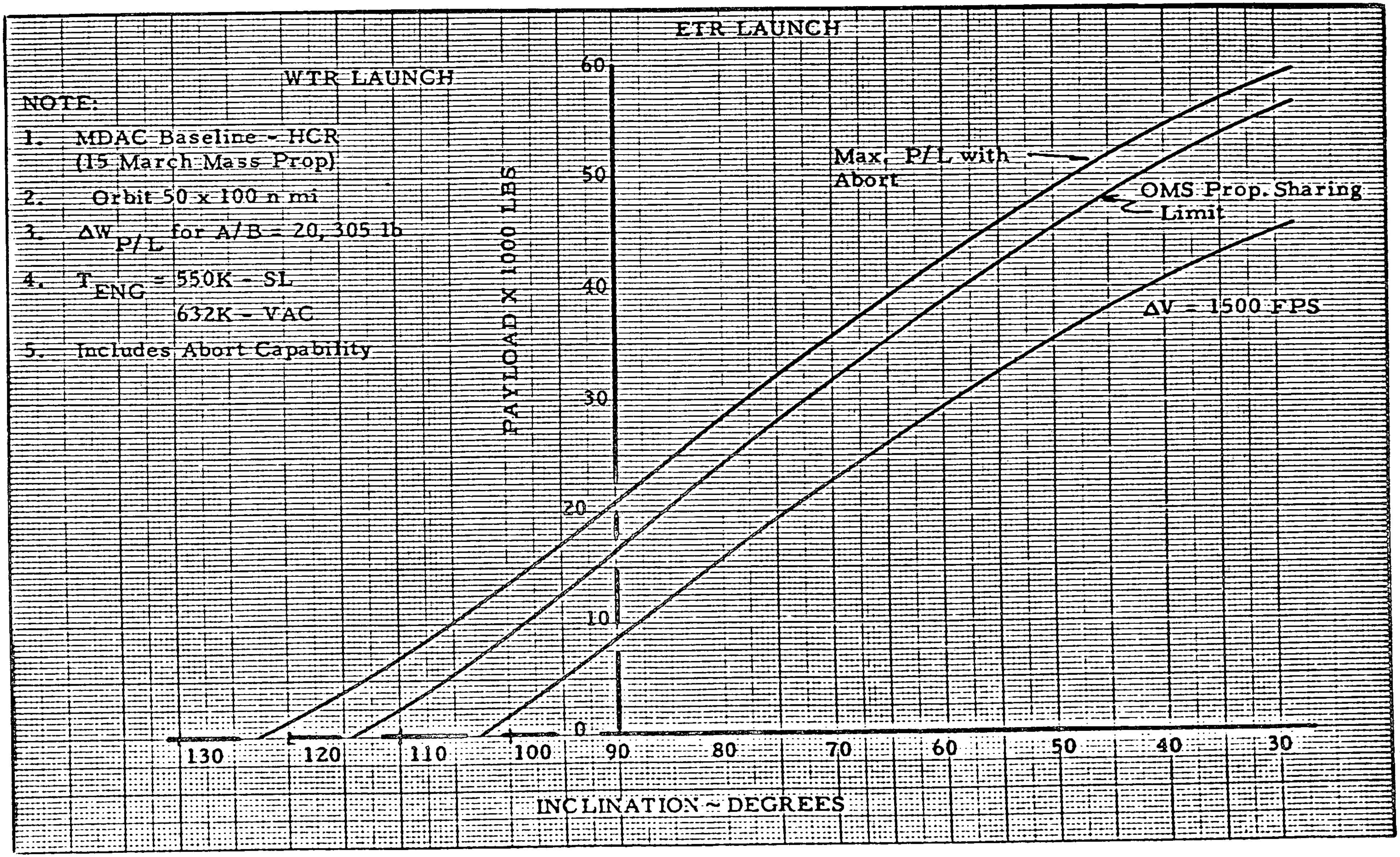


Figure 4-17. Space Shuttle Performance Capability Payload Versus Inclination, Two-Stage Fully Reusable

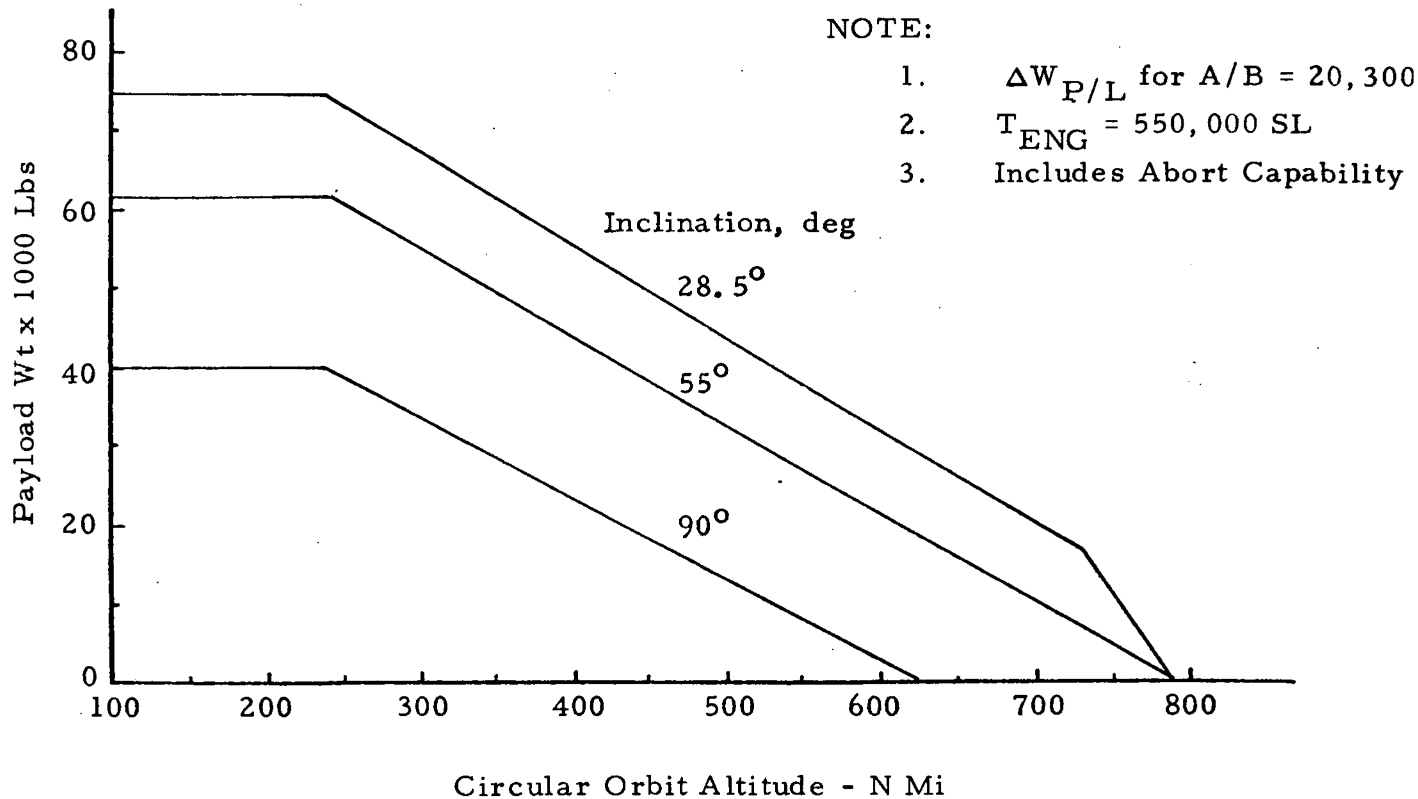


Figure 4-18. Space Shuttle Performance Capability
Payload Versus Circular Orbit Altitude, Two-Stage Fully Reusable

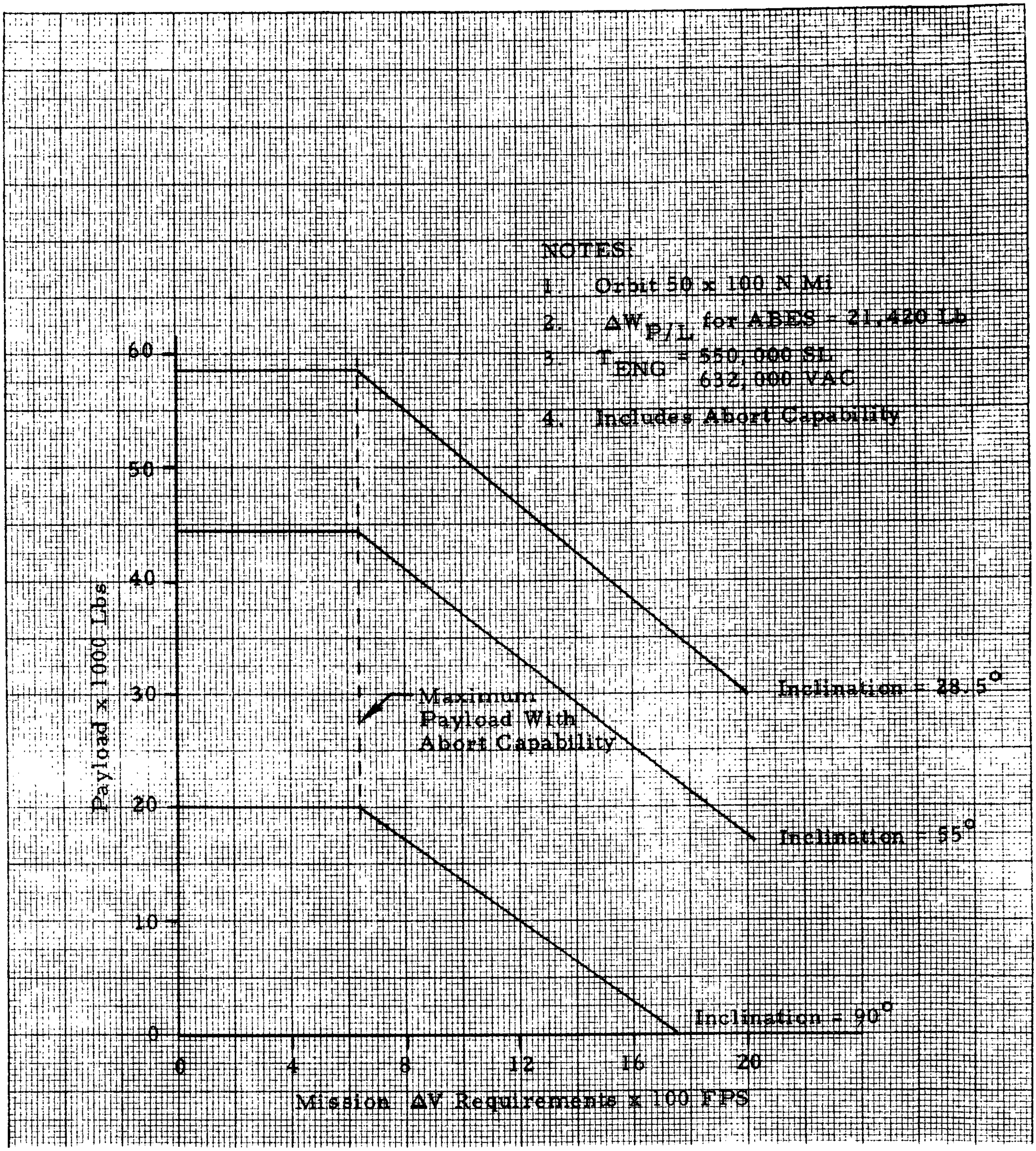


Figure 4-19. Space Shuttle Performance Capability
Payload Versus Mission Velocity, External Tank Orbiter

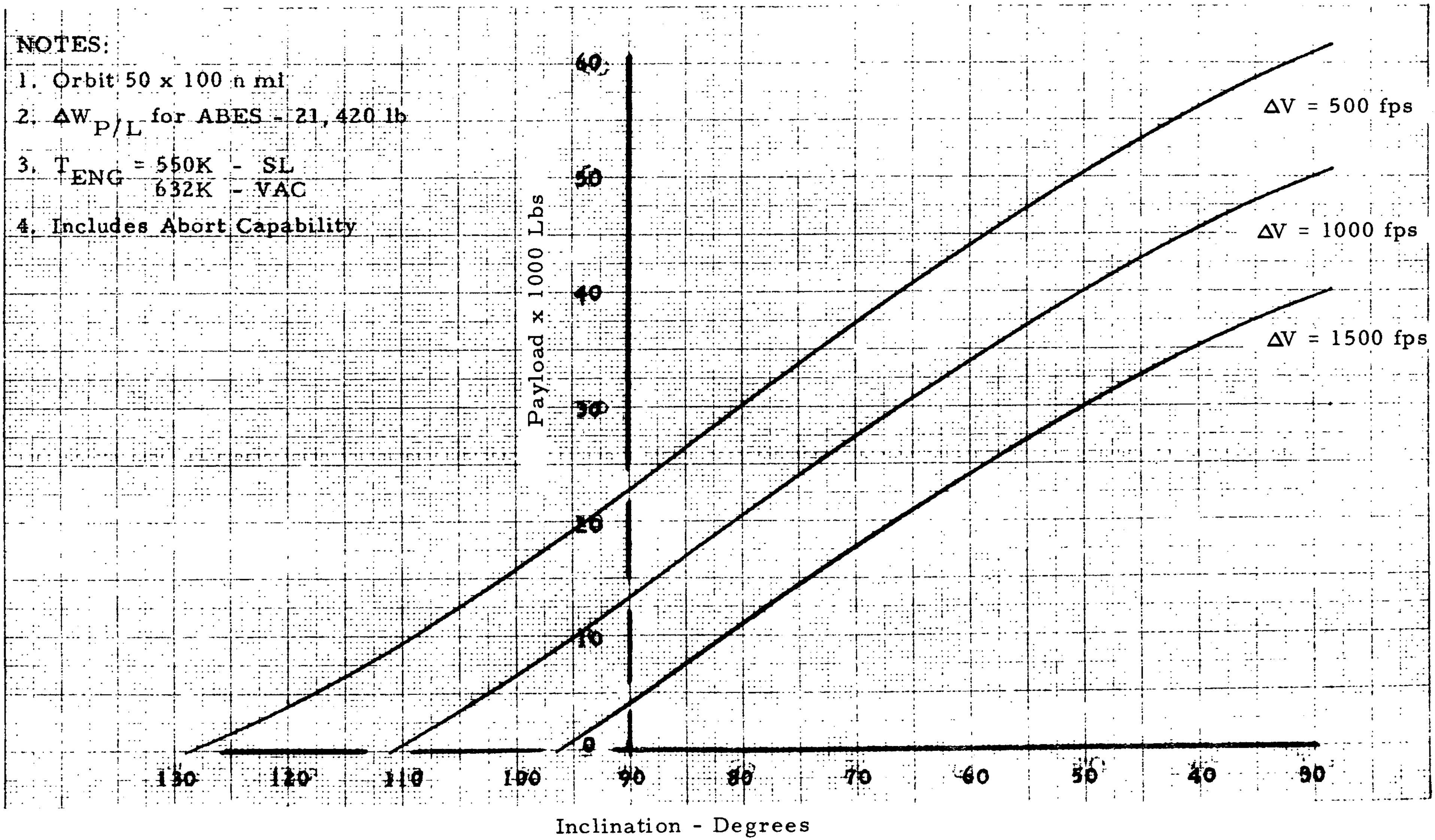


Figure 4-20. Space Shuttle Performance Capability
Payload Versus Inclination, External Tank Orbiter

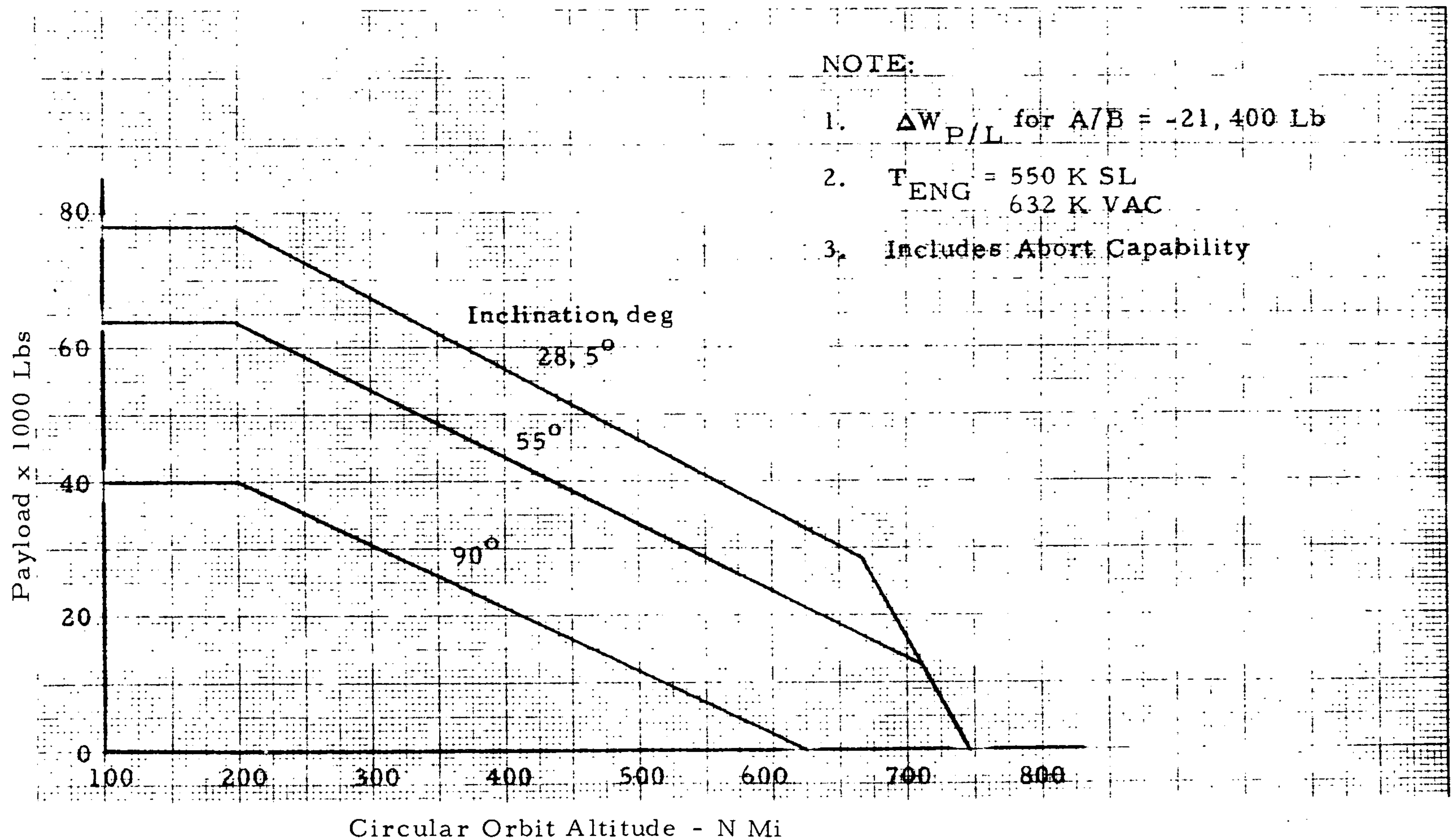


Figure 4-21. Space Shuttle Performance Capability
Payload Versus Circular Orbit Altitude, Orbiter External Tank (OET) Configuration

5. FURTHER ANALYSIS OF STUDY A FINAL DATA

This section describes the additional studies conducted on the Study A final data during the three month extension period from July 1, 1971 through September 30, 1971. During this three month extension period, numerous changes were made in the Final Report data from that released in the earlier draft versions of the Final Report. The most significant change was the deletion of certain DoD payload cost considerations because of insufficient data to support the analysis and concern that the draft data in these areas may be grossly in error. As a result of these changes, a major portion of the cost analyses performed in this extension period are no longer valid. The results of the analyses, based on the preliminary draft final data, are therefore not presented in this report. Paragraph 5.1, however, describes some of the studies conducted to indicate the level of effort that was expended on these preliminary data. Studies on the corrected final data are described in Paragraph 5.2, and the results of these studies are presented herein.

5.1 STUDIES PERFORMED ON THE PRELIMINARY DRAFT FINAL DATA

A brief summary of the studies conducted on the preliminary final data are presented in this section. As previously mentioned, the study results are not documented as the changes made to the final data partially invalidate these results.

A major effort was expended on comparing the results of the Mid-Term Report with the Rough Draft (Preliminary Data) Final Report. The reason for this comparison was to verify the economic benefits of the Space Shuttle as borne out by the Mid-Term Report. A rigorous comparison of the individual space program total costs from midterm to preliminary final analysis was not possible due to the many changes between the two analyses. One major difference was the smaller traffic model associated with the final analysis from that considered for the midterm. The reduction in the traffic model was influenced by elimination of unnecessary satellite redundancy and a 12 year mission model, rather than the 13 year model as used in the Mid-Term Report. Further mission model changes resulted in deletion of some space programs, addition of others, and revision of launch rates, dates and payload weights and sizes. Additional important differences were the inclusion in the final analysis of an accounting of: (1) the estimated effect of launch vehicle reliability (failure rates), (2) intact abort for the Space Shuttle, and (3) the ability of the STS to retrieve payloads suffering failure in the first 10 hours of operation (payload infant mortality). Tables 5-1 through 5-3 summarize the primary changes in the analysis from the Mid-Term to the Final Report. Considering these major differences between the mid-term and final analyses, several different approaches were taken to compare the two studies. Initially total system costs and cost streams were compared on an agency-by-agency basis to ascertain the cost differences between the two study efforts. Further detailed cost comparisons included payload RDT&E and investment costs, launch vehicle costs, STS cost savings relative to the current expendable systems and the new low cost expendable system, etc. Detailed studies were conducted of the cost ratios (STS/current expendable system) on a program-by-program basis for the mid-term and final analyses to further ascertain any inherent study differences. Payload weights (spacecraft and mission equipment) versus costs were also investigated for both the Mid-Term and Final Reports on an individual program basis. It was noted that the heavier payloads generally resulted in a greater STS payload cost savings, and several of these expensive programs in the mid-term analysis were deleted from the final analysis. In general, though total system and individual costs did differ, a similarity of the direct operating costs between the Mid-Term and Final (preliminary) Rough Draft Report was apparent when the two analyses were compared on an equal launch rate basis during a steady state period of the fully operational phase of the STS (1982-1988).

Cost analyses were conducted on the preliminary final data to investigate the relationship of the various cost related factors. These analyses included an investigation of the launch vehicle and payload cost impact associated with launch vehicle reliability and payload infant mortality; a review of the cost effect of the low cost payloads, including the impact of the payload weight and cost variations on total program costs; and the effect of the payload mean mission duration on costs.

Detailed payload cost studies and data cross-checks were also conducted to ascertain the consistency and accuracy of the cost models and data inputs. These studies included satellite unit recurring costs versus satellite weight, payload cost per pound versus satellite weight, payload tracking, telemetry and control weight versus total weight, payload selection checks, etc. These studies all tended to verify the consistency of the cost model, and the cost output data.

5.2 STUDIES PERFORMED ON THE FINAL DATA

A comparison of the Mid-Term Report results with the Final Report was made using the final data. The comparison was based on average yearly costs during a steady state period of the fully operational Space Shuttle era (1982-1988). The payload costs for two DoD missions were deleted from the mid-term analysis to make it comparable with the final analysis. The results are shown on Table 5-4. The total direct operating costs (DOC) on a yearly basis are shown to be quite similar between the mid-term and final results.

Additional analyses were conducted on the final cost results, on an average yearly DOC basis, to gain further insight into the relative cost breakdowns. Table 5-5 presents the DOC for the Current Expendable Launch Vehicle System and the STS, with the difference in costs being the savings associated with the use of the STS. The "other" column on this table refers to the costs associated with the Non-NASA and DoD programs combined. Also shown on the same table is the percentage of DOC savings associated with the following parameters: lower launch costs, increased launch vehicle reliability, payload retrieval and reuse capability, and use of the low cost payload designs. A further DOC cost breakdown is presented in Table 5-6 where the average cost per year is divided into payload RDT & E, payload investment and payload operations costs, and launch vehicle costs. Table 5-7 presents the average yearly cost increases associated with the addition of the sortie missions. This table points out the small impact on direct costs associated with rather large increases in the mission model traffic when operating with the STS.

A detailed analysis was conducted of the reliability effects (i.e., launch vehicle reliability and infant mortality) on the total system direct operating costs. The methodology for estimating the reliability effects on system costs was first defined, and then incorporated into the computer program to determine individual program direct costs. The results are presented in Volume III, Appendix A of the Integrated Operations/Payloads/Fleet Analyses Final Report, showing individual program direct operating costs and total system summary DOC with reliability effects included. The methodology utilized to incorporate the reliability losses is described in Volume V of the same final report. Table 5-8 summarizes the percentage increase in DOC resulting from consideration of the reliability effects for all of the cases considered.

An investigation of the mission model payload activity was made for the Final Report. Figure 5-1 presents the results in terms of on-orbit payload population per year and the average payload launch rate per year for the baseline mission model. Also included on this figure for comparison purposes are the USA and USSR average launch rates for the years 1962 through 1970. It is interesting to note that the baseline mission launch rate is comparable to the USSR launch rates from 1962-1970, but less than the USA launch rates for that same period. Furthermore, though not apparent on the figure, the USSR launch rate is sharply increasing every year with an extrapolated indication of a much higher launch rate than the current study baseline model for the 1982-1990 time period.

Some studies were conducted of individual program costs, using the Current Expendable Launch Vehicle System and the STS, to emphasize relative cost comparisons. Figures 5-2 and 5-3 present the program direct cost streams associated with the Non-NASA Polar Earth Resources Program for the Current Expendable System and the STS. The costs are broken down into Payload RDT & E, payload investment, payload operations and launch vehicle direct cost. This figure points out the particularly large payload investment savings that can be achieved with the STS for an on-going operational type of program. Though payload investment savings can also be important for smaller research oriented programs, they become the major cost savers for most of the operational programs.

In addition to the above described studies performed during the three month study A extension period, several briefings were presented in support of the NASA Space Shuttle efforts. The following listing presents briefings that were presented or supported by The Aerospace Corporation:

<u>Aerospace Presentations</u>

- PSAC Space Shuttle Panel Briefing, 15 Aug. 71
- Dr. Naka, Office of Under Secretary of the Air Force, 16 Aug. 71
- GAO Briefing, 25 Aug. 71
- Col. Tiernan, SAMSO, 24 Aug. 71
- Col. Davis, SAMSO, 24 Sept. 71
- Florida Contractors, 29 Sept. 71

<u>Aerospace Supported</u>

- LMSC Presentation at GSFC, 22 Sept. 71

Table 5-1. Primary Changes in Analysis - I

MID-TERM (DECEMBER 1970) TO FINAL (JUNE 1971)

	Source	Mid-Term	Final	Cost Effect on Final Analysis
PAYLOAD TRAFFIC[1]	NASA (& DoD)			Reduced Payload Savings Potential Through Reuse
Captured/Year, Average		74	64	
Costed/Year, Average		74	54	
LMSC PAYLOAD EFFECTS (Shuttle Launched 2 Year SEO Satellite)	LMSC			
Weight and Volume % Unit Cost Reduction		20	19	Negligible
Refurbishment Cost % of Unit Cost		30[2]	39	Increase Payload Refurbishment Cost
Shuttle Developed Payload RDT&E Hardware Reduction		No Data	1 Equivalent Unit	Reduction in Current Reusable Payload RDT&E Costs

(1) Baseline Mission Model

(2) Estimate was 30-50, 30% applied to if satellite developed (or redeveloped) for Shuttle

Table 5-2. Primary Changes in Analysis - II

MID-TERM (DECEMBER 1970) TO FINAL (JUNE 1971)

	Source	Mid-Term	Final	Cost Effect on Final Analysis
Additional Payload Effects				
Launch Vehicle Failures	Aerospace	No Data	3%	Reduced STS Payload Investment. Increased Expendable Launch Vehicle Recurring Cost
Payload Infant Mortality	Planning Research Corporation	No Data	6%	Reduce STS Payload Investment
Increase Spacecraft Mean Mission Duration (MMD) Through Redundancy(1)	Aerospace	No Data	Up to 6 Years MMD	Reduce Payload Refurbishment Costs
Payload Programs With Large STS Systems Savings Potential (Savings > $400M)	Mission Model	6	0	Reduced Potential for Payload Savings and Low Cost Ratios

(1) For Spacecraft With Short Duration Experiments

Table 5-3. Primary Changes in Analysis - III

MID-TERM (DECEMBER 1970) TO FINAL (JUNE 1971)

	Source	Mid-Term	Final	Cost Effect on Final Analysis
SPACE SHUTTLE				
Gross Liftoff Wt, Lbs	NASA	4.2	4.6	Increase Space Shuttle Non-recurring Costs
Flight Rate Buildup Period, Years	NASA/Aerospace	1	3	Increase Recurring Costs, 1979-1981
Useful Ceiling, N Mi	NASA/Aerospace	~ 300	~500	Decrease Recurring Costs
IOC, Year	NASA	1978	1979	Delay Shuttle Efforts 1 1/2 Years
Performance (ABE'S Out)	NASA			
100 N Mi East, Lbs		72K	65K(1)	None
100 N Mi South, Lbs		40K	40K	None
Payload Limitations	NASA			
Payloads Per Flight Stacking in Payload Bay		No Limit No Limit	3 Max None	Increase Flight Rate, Recurring Costs
SPACE TUG	Aerospace			
Fleet Size		35	11	Decrease Non-Recurring Costs
IOC		1978	1979 1985	Increase Recurring Costs
T-III LAUNCH SUPPORT COSTS	Aerospace	$6.0M	$4.2M	Decrease Recurring Costs

(1) Required, Up to 79K With Orbiter Engine Throttling

Table 5-4. Comparison of Mid-Term and Final Analysis Results
Average Costs in 1970 $ for Fully Operational Space Shuttle Era (1982-1988)

BASELINE MISSION MODEL

	STS/PAYLOAD COSTS, $B/YEAR	
	MID-TERM [1]	FINAL [1]
SYSTEM COSTS	2.05	2.14
DIRECT OPERATING COSTS (DOC)		
NASA	1.19	1.30
OTHER	0.82	0.70
TOTAL	2.01	2.00

[1] SUPPORT MISSION PAYLOAD COSTS NOT INCLUDED

Table 5-5. Average Direct Operating Costs for Fully Operational Space Shuttle (1982-1988)

	SPACE SYSTEM DOC $B/YEAR (1)	NASA DOC $B/YEAR	OTHER DOC $B/YEAR (1)
CURRENT EXPENDABLE LV SYSTEM	3.41	2.14	1.27
STS	2.00	1.30	0.70
COST SAVINGS WITH STS	1.41	0.84	0.57

SPACE SYSTEM COST SAVERS

	% OF DOC SAVINGS
LOWER LAUNCH COSTS	43%
INCREASED LAUNCH VEHICLE RELIABILITY	3%
PAYLOAD RETRIEVAL (2) AND REUSE	49%
LOW COST PAYLOAD DESIGN	5%

(1) SUPPORT MISSION PAYLOAD COSTS NOT INCLUDED

(2) INCLUDING PAYLOAD INFANT MORTALITY EFFECTS

Table 5-6. Average Direct Costs for Fully Operational Space Shuttle Era (1982-1988), $ 1970

BASELINE MISSION MODEL (1)

	$ B/YEAR	%
PAYLOAD RDT&E	0.65	32.5
PAYLOAD INVESTMENT	0.34	17.0
PAYLOAD OPERATIONS AND REFURBISHMENT	0.71	35.5
LAUNCH COSTS	0.30	15.0
TOTAL	2.00	100%

(1) Support Mission Payload Costs Not Included

Table 5-7. Effects of Sortie Missions on Results
Average Data for Fully Operational Space Shuttle Era (1982-1988)

	DIRECT COSTS $B/YEAR (1970$)	SHUTTLE FLIGHTS/YEAR
BASELINE MISSION MODEL	1.30	58*
MISSION MODEL WITH SORTIES	1.38	67*

* Does Not Include Reliability Effects (i.e., Assumes a Success Model)

Table 5-8. Reliability Effects on Total Program Direct Costs

CASE	% INCREASE IN DIRECT COSTS DUE TO RELIABILITY EFFECTS
A	6.6%
B	6.5%
C	2.6%
C-1	2.6%
C-2	4.1%
K	2.8%

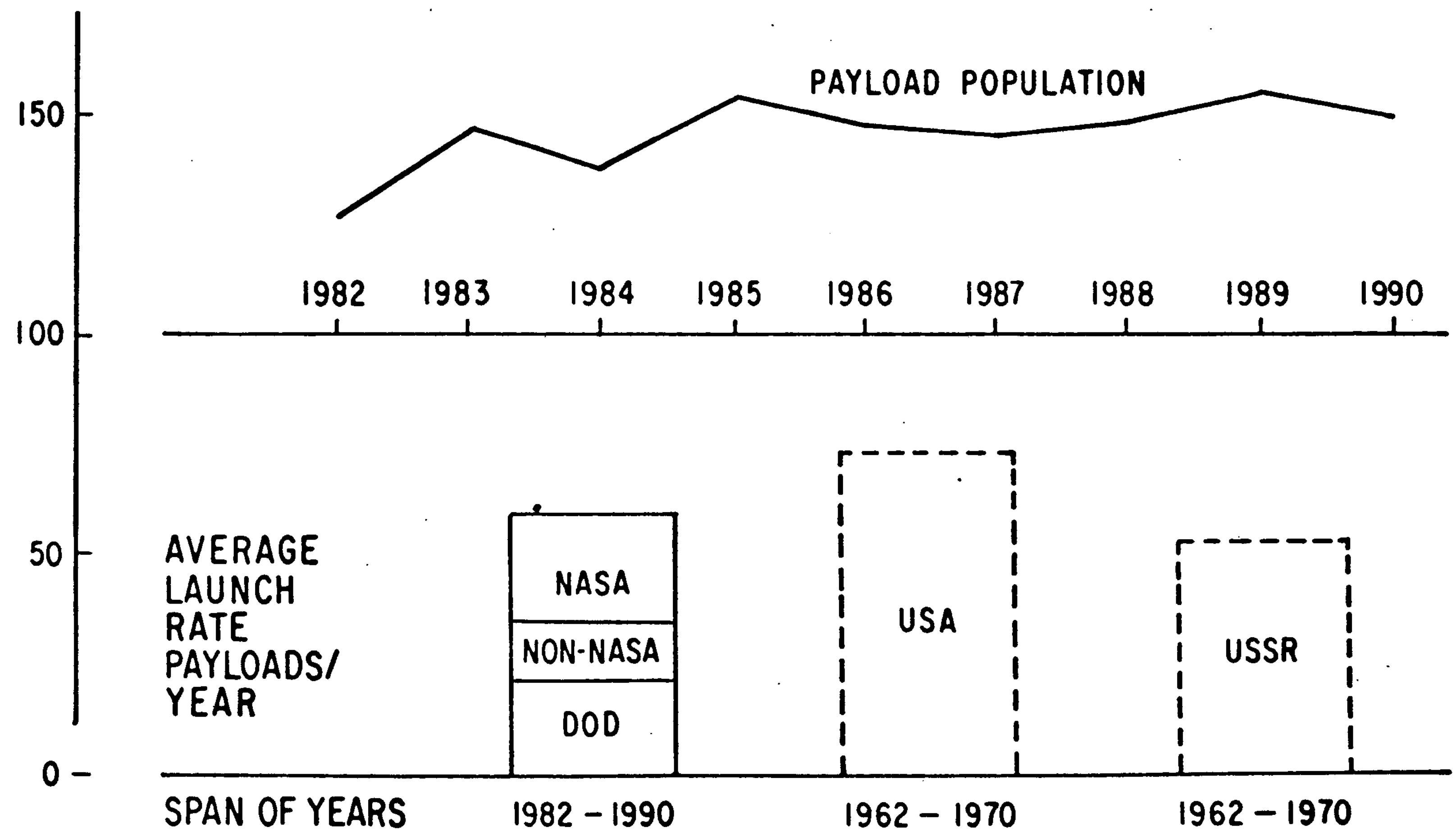


Figure 5-1. Mission Model Payload Activity Level

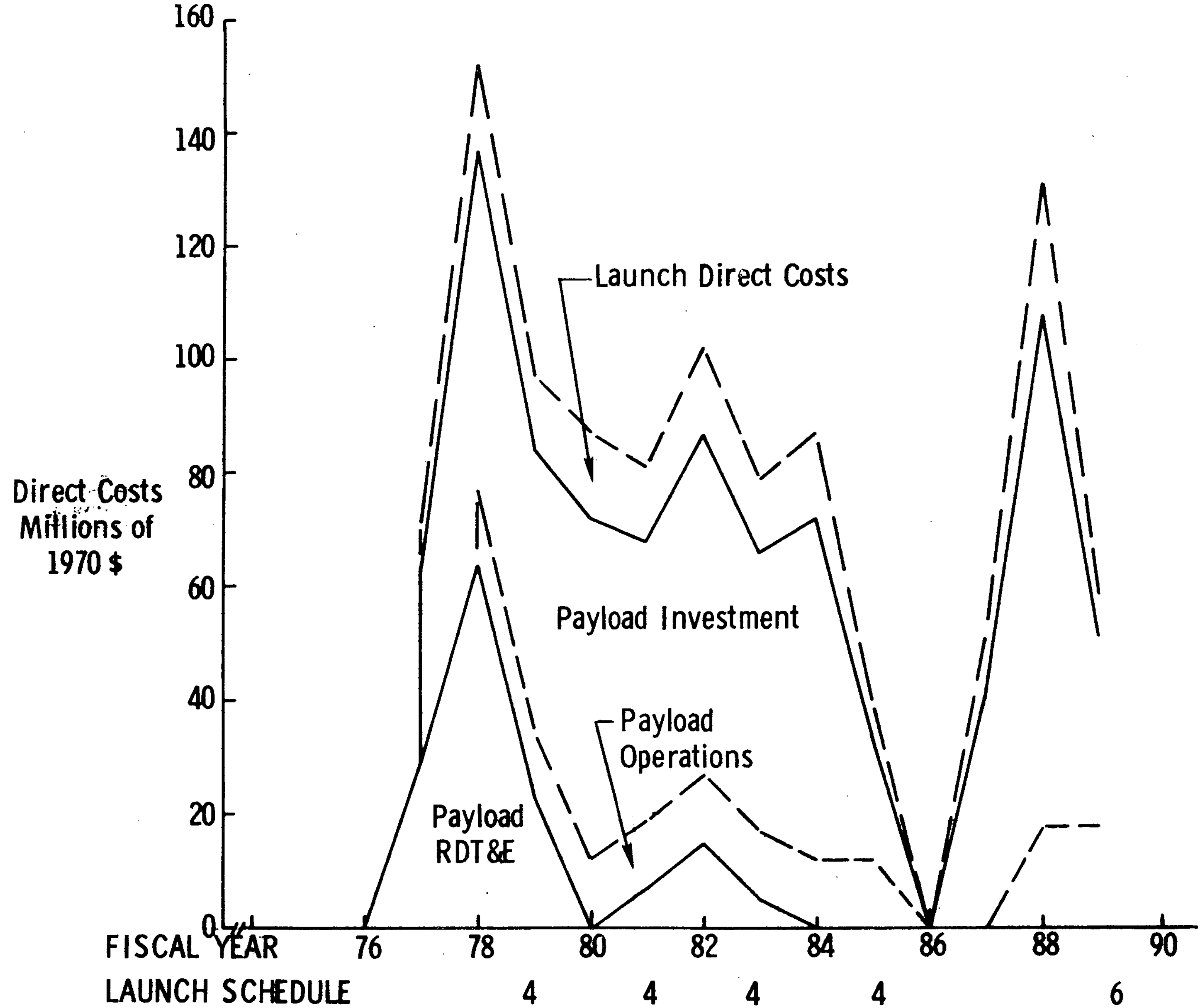


Figure 5-2. Polar Earth Resources Program Funding Direct Costs, Current Expendable Launch Vehicle Fleet

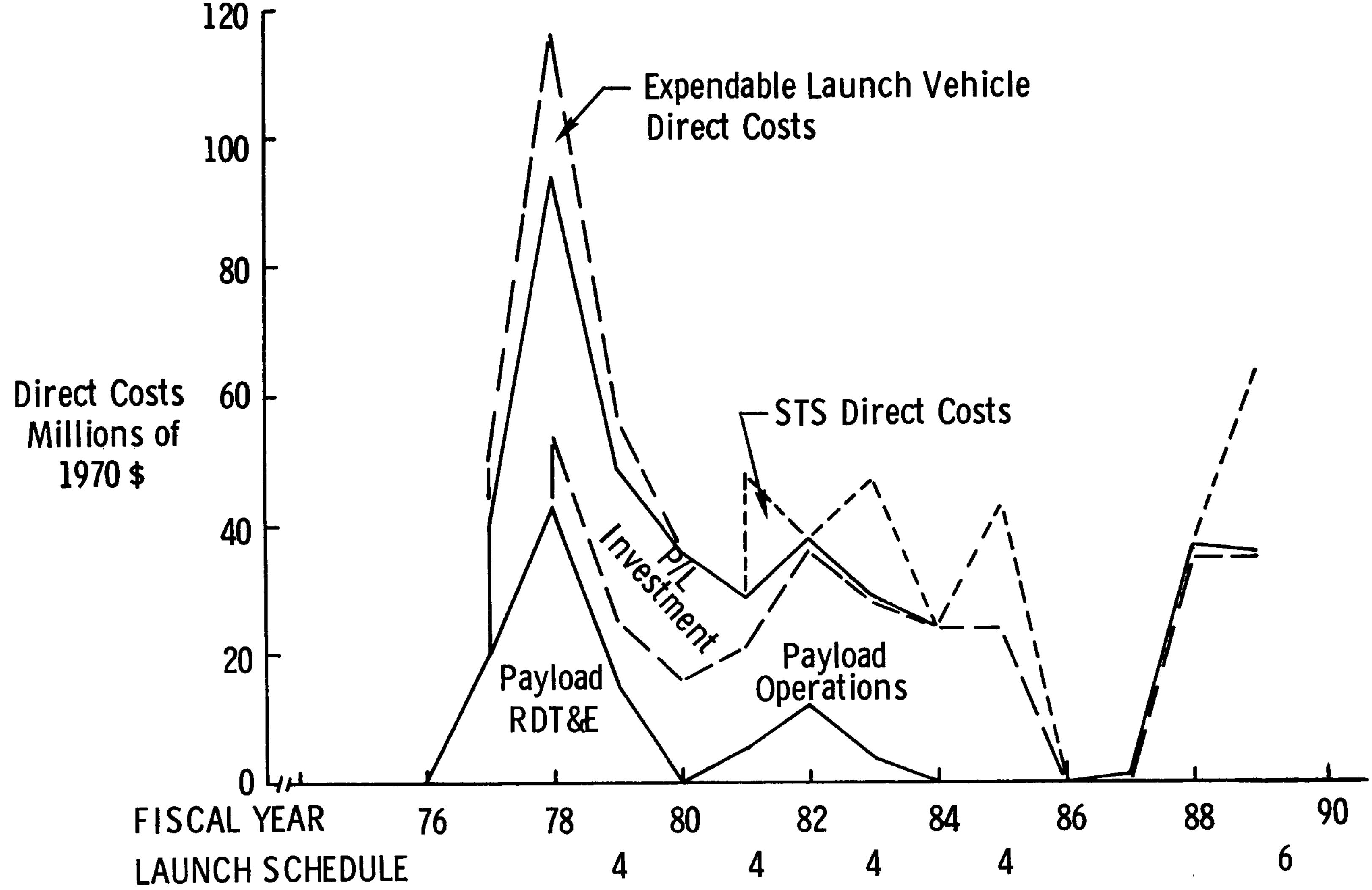


Figure 5-3. Polar Earth Resources Program Funding Direct Costs, STS Fleet

APPENDIX A

DERIVATION OF EXPRESSION FOR AVAILABILITY OF A SATELLITE USING THE WARNING SYSTEM

The average availability, A, of a system which can exist in either of two states, operating satisfactorily or not operating, can be expressed by the following equation:

$$A = \frac{T - T_N}{T} \tag{1}$$

where T = time period of operation of the system over which availability is to be determined

T_N = integral of time periods during T that the system is not operating.

A part of the strategy of using the warning system with a satellite is the inclusion of regular, scheduled satellite refurbishments. The operating satellite is removed from duty on a regular schedule and replaced with a satellite of equal expected lifetime (MMD). There is no loss of the satellite's function during the changeover because the replacement satellite is put into operation before the operating satellite is removed from duty.

Because of this scheduled refurbishment plan, the availability of the satellite over any time period is determined by its availability during each refurbishment interval, T_R. This assumes that T is greater than T_R and that availability during the fractional part of a refurbishment interval occurring at T, when T is not evenly divisible by T_R, is the same as that during a full refurbishment interval.

Constant satellite failure rates are assumed. The failure rates of satellites and subsystems with redundancy are variable, however. Therefore, assumption of constant satellite failure rates is an approximation. It is an acceptable approximation in many cases, however, because a constant failure rate can be set equal to the time average of the real values of the failure rate. This approach leads to acceptably accurate estimates of the number of failures. An example is given in Figure A-1.

The reliability of a system with constant failure rate λ at any time t is

$$R\ (t) = e^{-\lambda t} \tag{2}$$

The integral of the reliability over a period of time is the MMD for that time period. For a warning set satellite, the time period of interest is the refurbishment interval, T_R.

Therefore,

$$MMD\ (T_R) = \int_0^{T_R} e^{-\lambda t}\, dt = \frac{1 - e^{-\lambda T_R}}{\lambda} \tag{3}$$

Cross-multiplying Equation (3) and recognizing that $e^{-\lambda T_R} = R(T_R)$ by Equation (2), it is found that

$$\lambda = \frac{1 - R(T_R)}{M(T_R)} \tag{4}$$

where $M(T_R)$ = abbreviation for MMD (T_R).

Equation (4) represents the failure rate of an arbitrary set of subsystem elements during the refurbishment interval, T_R. λ_A can be defined as the failure rate of all the satellite subsystem elements not in the warning set and can be written as shown in Equation (5). The subscript A has been added to R and M of Equation (4).

$$\lambda_A = \frac{1 - R_A\ (T_R)}{M_A(T_R)} \tag{5}$$

Similarly, λ_W can be defined for a whole satellite, with warning set logic being used for the warning set elements, as follows:

$$\lambda_W = \frac{1 - R_W(T_R)}{M_W(T_R)} \tag{6}$$

But λ_W is not a satellite failure rate in the classical sense. This is because warning set logic is used for the warning set elements. λ_W is instead a combined rate of actual satellite failures from non-warning set elements, plus warnings from the warning set elements. Thus, λ_W includes λ_A. The warning rate from the warning set elements is given by

$$\lambda_{WW} = \lambda_W - \lambda_A \tag{7}$$

The probability of a satellite failure during a Shuttle delay period, H, is

$$P = 1 - R_S(H) \tag{8}$$

where $R_S(H)$ = reliability of the satellite at the end of interval H using "normal" logic (not warning set logic) for the warning set.

A Shuttle delay period is the time period between a signal indicating that the satellite is failing or has failed and the time that the replacement satellite is operating. The major portion of Shuttle delay is assumed to consist of waiting to schedule a trip on the Shuttle (and Tug).

Equation (8) applies to any interval of duration H within the refurbishment interval. The number of warnings issued by the warning set multiplied by P of Equation (8) gives the expected number of times that a failure is experienced by the satellite during all intervals H that replacement satellites are being put into orbit.

Because of the assumption of a constant failure rate, satellite failures occurring during an interval H can occur anywhere in the interval with equal probability. They therefore occur, on the average, at H/2, thereby producing outages that average H/2 in duration.

The total outage experienced by a warning set satellite can now be expressed as the total from two sources. The first is the expected number of failures occurring in the non-warning set elements times H. The second is the expected number of warnings sounded by the elements in the warning set, times the probability that a failure will occur during the interval H while a replacement satellite is on its way, times the average outage duration.

The expected number of failures is the failure rate times the time. For the non-warning set elements,

$$E_A = \left[\frac{1 - R_A(T_R)}{M_A(T_R)} \right] T_R \tag{9}$$

For the warning set elements, the expected number of failures is

$$E_W = \left\{ \left[\frac{1 - R_W(T_R)}{M_W(T_R)} \right] - \left[\frac{1 - R_A(T_R)}{M_A(T_R)} \right] \right\} \left[1 - R_S(H) \right] T_R \tag{10}$$

It is convenient to make the following definitions:

$$F_A = \left[\frac{1 - R_A(T_R)}{M_A(T_R)} \right] \tag{11}$$

$$F_W = \left[\frac{1 - R_W(T_R)}{M_W(T_R)} \right] \tag{12}$$

3 8

F_A and F_W are equal to λ_A and λ_W in this derivation, but the symbols are changed because subsequent usage can consider F_A and F_W in a more general sense than λ_A and λ_W would normally be used.

It is now possible to write the availability of the warning set satellite. Beginning with Equation (1) and using the word description of satellite outage given earlier, it can be written that

$$A = \frac{T_R - F_A T_R H - (F_W - F_A) \left[1 - R_S(H)\right] (T_R) \frac{H}{2}}{T_R} \tag{13}$$

Cancelling out the T_R's and rearranging terms results in

$$A = 1 - H \left\{ F_A + \frac{F_W - F_A}{2} \left[1 - R_S(H)\right] \right\} \tag{14}$$

This expression for the availability of a warning set satellite is believed to be a very good approximation.

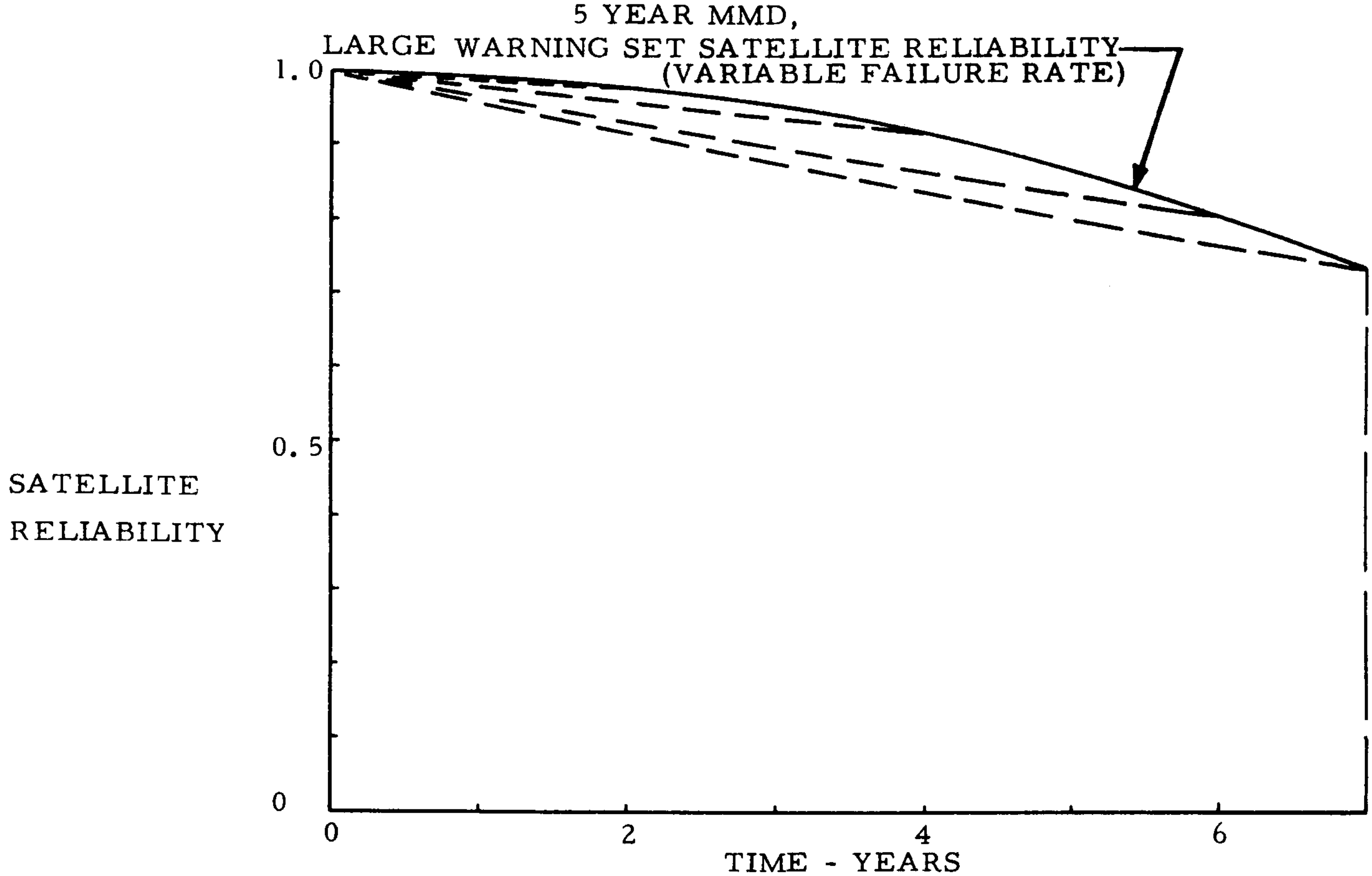


Figure A-1 (a). Warning Set Satellite Reliability Curve, plus Reliability Curves for Assumption of Constant Satellite Failure Rates for T_R's of 2, 4, 6 and 7 Years

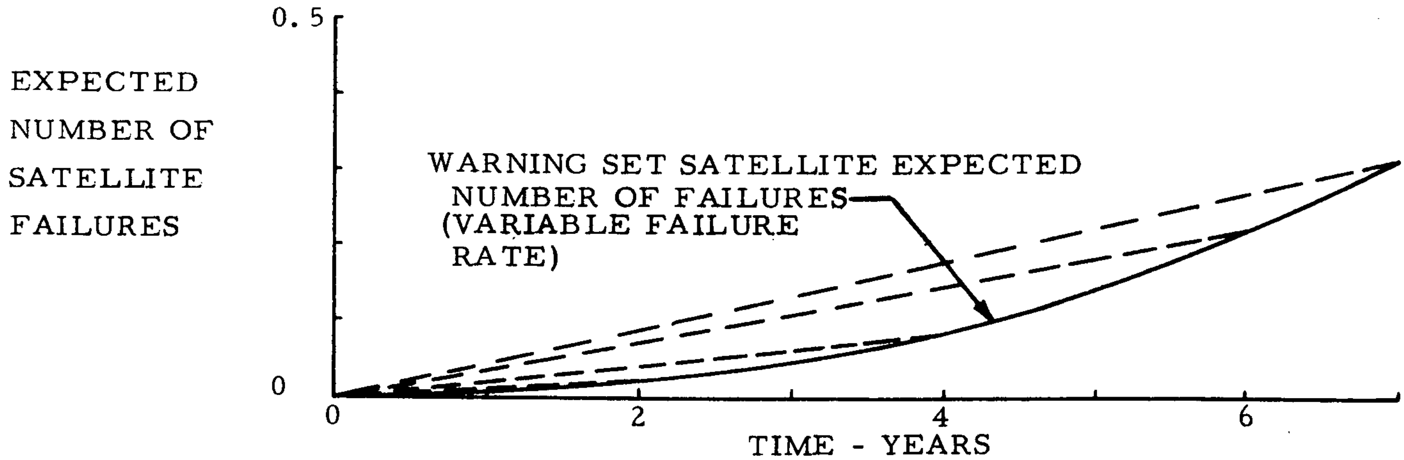


Figure A-1 (b). Warning Set Satellite Expected Number of Failures, plus Constant Failure Rate Approximations for T_R's of 2, 4, 6 and 7 Years

NOTE: — — — = CONSTANT FAILURE RATE

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